Energy Consumption and Carbon Footprints of New Zealand Dairy Systems: Comparison of Pastoral and Barn Dairy Farming Systems

A thesis

submitted in partial fulfilment

of the requirements for the Degree of Doctor of Philosophy in

Environmental Management and Sustainable Development

at

Lincoln University

by

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Lincoln University

2019

Declaration

The sections of this thesis have been submitted (through minor changes depending upon journal requirements) and accepted for publication and/or presented in conferences in advance of submission of this thesis:

Papers Published

1. Ilyas, H. M. A., M. Safa., A. Bailey., S. Rauf and A. Khan. 2020. Energy Efficiency Outlook of New Zealand Dairy Farming Systems: An Application of Data Envelopment Analysis (DEA) Approach. Journal of “Energies” (Published).
2. Ilyas, H. M. A., M. Safa., A. Bailey., S. Rauf and M. Pangborn. 2019. The Carbon Footprint of Energy Consumption in Pastoral and Barn Dairy Farming Systems: A Case Study from Canterbury New Zealand. Journal of “Sustainability” (Published).
3. Ilyas, H. M. A., M. Safa., A. Bailey., S. Rauf and M. Cullen. 2019. Evaluation of Energy Footprint of Pastoral and Barn Dairy Farming Systems in New Zealand. Paper published in 22nd International Farm Management Association (IFMA) Congress Proceedings, held at Launceston, Tasmania, Australia on 3-8 March 2019.

Conference Presentations

1. Ilyas, H. M. A., M. Safa., A. Bailey., S. Rauf and M. Cullen. 2019. Evaluation of Energy Footprint of Pastoral and Barn Dairy Farming Systems in New Zealand. Paper presented in 22nd International Farm Management Association (IFMA) Congress, held at Launceston, Tasmania, Australia on 3-8 March 2019.

2. Ilyas, H. M. A., M. Safa and A. Bailey. 2016. Energy Consumption and Environmental Emissions of New Zealand Dairy Farming Systems. Paper presented in Lincoln University Postgraduate Conference 2016.

Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

Abstract

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Over the last years, New Zealand dairy farming has expanded both in dairying area and milk production and became more intensive in terms of energy inputs. The usage of higher energy inputs are responsible for significant direct and indirect fossil energy consumption, which produces carbon dioxide (CO_2) emissions both on-farm through consumption of fossil fuels in machinery and off-farm during the production of fertilizers and imported feed supplements inputs. The aim of this research study was to estimate and compare energy consumption, efficiency and related carbon footprints of New Zealand pastoral (PDFs) and barn dairy farming systems (BDFs). The estimation of energy use and associated carbon emissions (CO_2) will help to identify an energy and emission efficient dairy farming system for the future of the New Zealand dairy industry. Accordingly, the energy efficiency of both dairy systems was evaluated based on the Data Envelopment Analysis (DEA) approach.

The study was conducted on 50 dairy farms including 43 pastoral and 7 barns, in Canterbury, New Zealand. Canterbury represents 16% of the total dairy land and comprises 19% of total dairy cows of New Zealand. In this study, energy consumption was defined as energy involved to produce the milk until it leaves the farm gate. The data were collected through a survey questionnaire for the dairy season 2016-17. The energy inputs considered in this study are those involved in on-farm milk production excluding post-processing components.

On average, the energy consumption of pastoral (PDFs) and barn (BDFs) dairy systems was estimated as 50538 MJ ha^{-1} and 55833 MJ ha^{-1} respectively. In the total energy consumption, electricity (35.5%) and fertilizer (29.9%) were the main energy inputs in PDFs, while in BDFs, electricity (34.8%) and imported feed supplement (24.1%) were the leading energy inputs. The difference in total energy consumption was 5295 MJ ha^{-1} indicating that pastoral (PDFs) systems used 9.5% less energy compared to barn dairy farming systems (BDFs).

Energy related total annual carbon footprints (CO_2) of pastoral (PDFs) and barn (BDFs) dairy systems were equivalent to 2857 kgCO_2 ha^{-1} and 3379 kgCO_2 ha^{-1} respectively. In terms of individual energy input contribution to total carbon footprints, machinery (27%) and fertilizer (25%) were the major carbon sources in PDFs, while in BDFs, imported feed supplements (30%) and machinery (24%) were the dominant sources of carbon emissions. From a system comparative perspective, pastoral (PDFs) system have 15% lower carbon footprints than the barn dairy system (BDFs) with total difference of 522 kgCO_2 ha^{-1}.

Based on the Data Envelopment Analysis (DEA) approach, the energy efficiency results highlighted the average technical, pure technical and scale efficiencies of pastoral (PDFs) as 0.84, 0.90, 0.93 respectively and for barn dairy systems (BDFs) as 0.78, 0.84, 0.92 respectively, indicating that energy efficiency is slightly better in the PDFs systems compared to BDFs. Further, this study suggested energy auditing and usage of more renewable energy sources for on-farm energy efficiency improvement in both dairy systems.

Keywords*:* Energy Consumption, Carbon Footprints, Energy Efficiency, Pastoral Dairy Farming System (PDFs), Barn Dairy Farming System (BDFs), Canterbury, New Zealand

Acknowledgements

In the name of Allah, the Most Gracious and the Most Merciful. Alhumdulillah, all praises to Allah for the strengths and His countless blessings in completing this thesis.

This thesis would not have been possible without valuable contributions and support from my supervisors, family and friends, various people from Lincoln University and the dairy industry of New Zealand. Firstly, I would like to express my immense gratitude and appreciation to my supervisors, Dr. Majeed Safa and Professor Alison Bailey from Department of Land Management and Systems, Lincoln University, for their guidance, constructive criticism and academic advice. My research project benefited immensely from their valuable comments and suggestions at different stages of the PhD. They always guided me in the right direction, made me feel comfortable and helped me to overcome the problems that I faced during my PhD.

I would also like to thank Dr. Marvin Pangborn (farmer/ex-employee of Lincoln University), for his time and support in data collection for this project. Undoubtedly, this research would not have been possible without his sustenance. I am also grateful to Helen Thoday from DairyNZ for her efforts in getting barn dairy farms for this project.

I express my deep and sincere gratitude to my father Muhammad Ilyas, whose encouragement along with moral and financial support helped me to achieve my goal and my mother for her immense affection and prayers. I would like to proceed the acknowledgement by owing every meaningful word to my beloved wife Sara, who stood with me determined and helped me most to complete my research – I am humbly thankful to her. I am also delighted to thank my brother Ali and sisters for their support throughout my life.

Finally, I would like to thank all my friends from Pakistan and New Zealand for their support throughout my PhD. Especially, I would like to remember my friend Martyred Dr. Haroon Mahmood (May Allah exalt his rank in Jannah) and acknowledge his support and guidance during my tough times – sir you will be missed always.

Hafiz Muhammad Abrar Ilyas

Dedicated

To the martyred and those affected by the life changing incident in the Christchurch Mosque, New Zealand on Friday, 15th March 2019

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Abbreviations and symbols

ASABE	American Society of Agricultural and Biological Engineers
ASAE	American Society of Agricultural Engineers
BDFs	Barn Dairy Farming System
BCC	Banker Charnes Cooper
CCR	Charnes Cooper Rhodes
CRS	Constant Return to Scale
CO_2	Carbon Dioxide
CH_4	Methane
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
EP	Energy Productivity
FAO	Food and Agricultural Organization
FAR	Foundation for Arable Research
GHG	Greenhouse Gas
GJ	gigajoule
h	hour
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
J	joule
K	Potassium
Kg	kilogram
kWh	kilowatthour
L	Litre
LIC	Livestock Improvement Corporation
LUDF	Lincoln University Dairy Farm
MS	Milk solids
MED	Ministry of Economic Development
MfE	Ministry for the Environment

MPI	Ministry for Primary Industries
MJ	megajoule
N_2O	Nitrous Oxide
N	Nitrogen
OER	Overall Energy Ratio
P	Phosphorous
PDFs	Pastoral Dairy Farming System
PCE	Parliamentary Commissioner for the Environment
PTE	Pure Technical Efficiency
RMSE	Root Mean Square Error
S	Sulphur
SE	Scale Efficiency
t	Tonne
TE	Technical Efficiency
VRS	Variable Return to Scale

Chapter 1

General Introduction

1.1 Background of the Research

The world population is growing and according to the Food and Agriculture Organization (FAO), it is projected to increase from its current level of 7.6 billion to 8.6 billion in 2030 and is expected to reach 9.8 billion by 2050 (FAO, 2019; Schneider, 2010). So, the global food demand is expected to double by 2050. Today food security in terms of feeding this growing population is a significant challenge for the whole world. Therefore, the agricultural systems throughout the world will have to produce enough food to feed this growing population.

Globally, the agricultural sector plays an important role in the improvement of food security through contributing to the growth of the country's economies and reducing poverty (Pingali & McCullough, 2010). Dairy is an important enterprise within the agricultural sector (Muehlhoff, Bennett, & McMahon, 2013). Today dairy production is serving over 7 billion consumers and providing livelihoods for approximately 1 billion people living on dairy farms (Bailey, 2017). Moreover, the global milk and meat productions is expected to be more than double by 2050 compared to 1999 levels (Steinfeld et al., 2006), an increase that is being known as the Livestock Revolution (Devendra, 2002). Thus, dairying is an essential in the endeavour towards ending hunger, reaching food security and refining the nutritional value of diets in a sustainable manner.

Energy is a critical input and significant cost for dairy farming systems. Energy consumption in dairy farming systems comprises both renewable and non-renewable energy resources. It consumes large quantities of commercial energies such as diesel, electricity, fertilizer, irrigation water and machinery. Where there is efficient use of these energies, this can help to increase productivity and profitability along with reductions in environmental emissions and cost associated with milk production (Singh, Mishra, & Nahar, 2002; Todde, Murgia, Caria, & Pazzona, 2018b). However, the current situation of rising oil prices and declining energy resources has caused numerous challenges for all countries, particularly those that are highly dependent on fossil energy sources. Some estimations indicate that fossil energy sources have declined significantly and they will expected to be exhausted by the end of this century (Safa, 2011). Moreover, energy and environment are strongly correlated with each other; that means growing energy usage anywhere will be accompanied by increased adverse effects on the environment (Safa, 2011). It is acknowledged that air pollution, acid rain, and, especially, global climate change issues have been mostly triggered by greenhouse gas emissions from fossil fuel combustion. Under these scenarios, dairy farming systems need to reduce their energy consumption either by energy efficiency improvement or controlling their fossil fuel demands by using more renewable energy resources (solar, wind etc.).

In New Zealand, agriculture is a main component of the NZ economy, with exports from agricultural products such as meat and milk comprising more than 60% of the total value of the country's merchandise exports (NZAGRC/PGgRc, 2019). Within agriculture, dairy is one of the most important sectors of the New Zealand economy, comprising approximately one third of the nation's total export earnings (Wheeler, 2014). Over the previous decades, the NZ dairy industry has significantly expanded and intensified especially in Canterbury, both in terms of land area and number of milking cows (Statistics New Zealand, 2018). As consequences of dairy intensification, energy consumption has increased in New Zealand dairy farming systems (Podstolski, 2015). This higher energy consumption has caused several environmental challenges to New Zealand dairy farming systems.

Although dairying is a major contributor to the New Zealand economy (with export value $NZ13.4 billion), but it is also a main contributor to NZ's total greenhouse gas (GHG) emissions (DairyNZ & LIC, 2017b). Almost half of New Zealand's total greenhouse gas emissions can be attributed to the agricultural sector, with a significant proportion coming from the dairy sector (NZAGRC/PGgRc, 2019). Over the last few years, New Zealand dairy farming has been frequently developing more intensive systems of management, which involve more utilization of energy inputs (Parliamentary Commissioner for the Environment, 2004). These energy inputs are responsible for significant direct and indirect fossil energy consumption, which produce emissions of carbon dioxide both on-farm and off-farm (Todde et al., 2018b; Wells, 2001). The carbon dioxide emission along with other on-farm greenhouse gases emissions (such as CH_4, N_2O) cause numerous environmental challenges which are putting NZ dairy farming systems under huge public pressure both locally and internationally (Foote, Joy, & Death, 2015; Parliamentary Commissioner for the

Environment, 2016). Moreover, according to the Paris Accord agreement (Ministry for the Environment, 2019), New Zealand has committed to reducing its greenhouse gas emissions by 30% below 2005 levels by 2030. In response to the Paris Accord commitments, recently the New Zealand government introduced a “Zero Carbon Bill” for all industries including the dairy sector, which sets new emission reduction targets such as carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions having to be reduced to net zero by 2050, while methane (CH_4) emission has to be reduced up to 10% by 2030 (DairyNZ, 2019). So currently, reducing the greenhouse gas emissions from NZ dairy farming systems is a critical challenge for the NZ dairy industry, as the dairy sector alone is responsible for 22.5% of New Zealand’s total GHG emissions (DairyNZ, 2019). In this situation, identification of the dairy farming system with the minimum energy carbon footprints is necessary for the NZ dairy industry, in order to achieve future emission reduction targets.

Energy efficiency improvement is one of the most important aspects in regard to combating energy related challenges. Energy efficiency improvements not only contribute to the reductions of emissions and climate change, but also provide solutions for fuel resources restrictions (Varone & Aebischer, 2001). The study of energy flow and energy efficiency will consent us to recognise bottle-necks and, consequently, improve the production processes to reach systems with more energy efficiency. Scientists have considered and measured the energy efficiency of dairy farming systems. The dairy farming systems which vary in intensity, crop type, region and management have been evaluated based on energy efficiency indicators (Hosseinzadeh-Bandbafha, Safarzadeh, Ahmadi, & Nabavi-Pelesaraei, 2018; Uzal, 2013). Likewise some researchers evaluated the energy efficiency of farming systems and found a reduction in the energy output input ratio in case of more intensified systems, since the growth in the yield was less than the increase in the consumption of non-renewable energy resources (such as fossil fuels and fertilisers) (Kuesters & Lammel, 1999; Pimentel et al., 1975; Pimentel, Pimentel, & Karpenstein-Machan, 1999). According to Pimentel (2009), the energy efficiency of dairy production systems is lower than that of crop production. Moreover, there is insufficient knowledge about the energy efficiency of dairy production systems. In this regard, energy efficiency evaluation of dairy farming systems is necessary and will be helpful for identification of energy efficient dairy farming systems.

The New Zealand dairy industry is renowned for its traditional pasture-based dairy farming system (PDFs), where farmers aim to increase their profits by minimizing production costs through maximizing the proportion of grazed pasture in the diet of lactating cows (Basset-Mens, Ledgard, & Boyes, 2009; O'Brien, Capper, Garnsworthy, Grainger, & Shalloo, 2014). However, the intensification of this pasture-based dairy system over the last decades, as well as rising sustainability concerns due to the challenges of nutrient leaching and greenhouse gas emissions is of concern to many. One response to these challenges has been the introduction of the barn dairy system (BDFs) into New Zealand, in which animal shelter (the barn facilities) is used in combination with pasture grazing for the purposes of reducing soil damage, animal lameness and environmental impacts (Pow, Longhurst, & Pow, 2014). But the use of barn facilities requires further intensification of the system, in terms of stocking rate and energy inputs to make the system profitable, otherwise it is difficult to achieve both financial and environmental benefits simultaneously (Newman & Journeaux, 2015). Under these circumstances, energy use evaluation of New Zealand contrasting dairy systems is essential in order to identify energy efficient dairy farming systems for the future of the NZ dairy industry.

Therefore, the purpose of this study is to assess and evaluate the energy consumption, efficiency and associated carbon footprints (CO_2) of New Zealand pastoral and barn dairy farming systems in Canterbury, New Zealand. Further, an energy efficiency comparison was also performed between PDFs and BDFs dairy systems in order to identify the energy efficient dairy systems, along with benchmarking and optimum energy consumption estimation work. Furthermore, this study also developed a carbon footprint prediction model to predict energy related carbon emissions for Canterbury dairy farms.

1.2 Context of New Zealand Dairy Farming

The agriculture sector is one of the biggest export earners in New Zealand that contributes around 60% to merchandise exports (Statistics New Zealand, 2014). New Zealand's agriculture mainly developed on historic clearing of native forest and is mostly dominated by pasture-based farming systems such as beef, sheep and dairy systems. Among the agricultural sectors, dairy is the most influential sector in New Zealand with a total revenue of NZ$13.6 billion in the year 2016 (Ballingall & Pambudi, 2017). As a significant industry in

New Zealand, the dairy sector contributes a substantial amount to export value (37%) in both the primary sector and for all exports (29%) (Bailey, 2017). The New Zealand dairy industry is the world's largest exporter of milk, producing nearly 3% of the world's total milk production (Bailey, 2017). The amount of milk solids produced in New Zealand have increased over the last years, that is due to expansion of dairy industry both in land area used as well as developing more intensive farming practices (DairyNZ, 2017b).

Canterbury is one of the significant and influential regions of New Zealand, with dairying in the region valued at around NZ$2.3 billion in the years 2016-17. About 19% of NZ's total dairy cows are in Canterbury (905,076 cows) with an average herd size around 764 (DairyNZ, 2017b). The 16% of New Zealand's total dairy land belongs to Canterbury, with total land area around 271,102 ha (DairyNZ, 2017b). The majority of farms in Canterbury belongs in the owner-operated category with a total number of 914, while 270 farms represent share-milking type farming systems.

Compared to other NZ dairy regions, Canterbury has experienced strong growth in the number of dairy cows. Also, the scale of dairy farms in the South Island is greater than that of the North Island (both in terms of cow numbers and farm area), with twice the herds size compared to herds found in NZ more traditional dairy regions such as South Auckland and Taranaki (DairyNZ & LIC, 2017a). The stocking rates are also higher in the South Island. The national average stocking rate is 2.83 cows per hectare, whereas in Canterbury it is 3.37 cows per hectare (DairyNZ & LIC, 2009). This strong growth in the South Island has been supported by increased use of irrigated water, fertilizer applications and the shifting of land use from less intensive sheep and beef farming to dairying (Williams & Richardson, 2004).

1.2.1 Pastoral Dairy Farming System (PDFs)

New Zealand is renowned for its year-around outdoor pastoral grazing dairy system (PDFs), with heavy reliance on perennial ryegrass/white clover pasture species (Clark, Caradus, Monaghan, Sharp, & Thorrold, 2007; Moot, Mills, Lucas, & Scott, 2009). In most of the pastoral systems (PDFs), usually animals live in a set of paddocks, move within those paddocks for grazing and eating pasture and are then brought every day to milking parlours for harvesting their milk. In the PDFs system, direct grazing contributes around 90% of the animal feed demand, making it a low production cost system compared to international standards. The imported feed supplements are only used in the PDFs system, during times of low pasture production or insufficient pasture to meet feed demand (Bailey, 2017). Figure 1-1 shows some NZ's pastoral dairy farming systems (pictures taken by author during the farm visits):

Figure 1- 1: New Zealand Pastoral Dairy Farming System (PDFs)

New Zealand's dairy industry classified its pastoral dairy farming system (PDFs) into five different dairy systems (Systems 1 to 5), based on their feed supplements usage. The main reason to consider the feed supplements as a single variable for this system classification was to make a convenient comparison between farms of different regions (Hedley et al., 2006). Table 1-1 describes the DairyNZ systems classification for pastoral dairy systems of New Zealand:

Table 1- 1: New Zealand Dairy System Classification

System Type	**Classification**
System 1	All-grass self-contained dairy system, <4% imported feed
System 2	4-14% feed imported to supplement or for grazing off for dry cows.
System 3	10-20% feed imported to extend lactation (typically autumn feed) and for dry cows
System 4	20-30% feed imported, at both ends of lactation and for dry cows
System 5	20-55% feed imported used all year throughout lactation and for dry cows.

There is no justification that exists in the literature about this dairy system classification, instead it is just presumed by the NZ dairy industry. The reason for adoption of this classification was probably its easy application and simplicity of understanding by farmers. Currently, the main challenges to NZ PDFs systems are nutrient leaching and greenhouse gas emissions, putting pastoral systems under high scrutiny and public pressure.

1.2.2 Barn Dairy Farming System (BDFs)

The barn dairy farming system (BDFs), is a system in which dairy cows live inside a closed structure building for different durations of the year and the operations like animal feeding, milking, effluent management take place within that building. The barn dairy system (BDFs) is relatively new in New Zealand, but its number is increasing especially in the South Island (Pow et al., 2014). The main advantages of using barn systems in New Zealand are better soil protection, more control over climatic events and achieving higher milk production per cow (Pow et al., 2014). Compared to barn systems used in the USA and Europe, New Zealand barn systems are mostly used in combination with pastoral grazing, also named a "hybrid system" (Pow et al., 2014). Although, the barn system (BDFs) provides a number of animal welfare and environmental solutions (nutrient leaching control), the high installation and operating cost along with dependency on a volatile milk price to make the barn profitable may off-set its potential benefits. According to a Newman and Journeaux (2015) study, it is difficult to achieve both environmental and financial benefits of the barn system simultaneously. Figure 1-2 shows some Canterbury barn dairy farming systems (pictures taken by author during the farm visits):

Figure 1- 2: Pictures of New Zealand Barn Dairy Farming Systems (BDFs)

1.3 Synopsis of Energy Studies in New Zealand Dairy Farming

The initial study related to energy consumption in New Zealand dairy farming was documented by McChesney (1979). Prior to performing a main survey of North Island dairy farms, this study was conducted as a pilot study based on twelve town milk supply dairy farms. McChesney (1979) considered energy as direct, indirect and capital inputs and data were collected through farmers' interviews for the season 1976-77. The outcome of his study identified total energy inputs as 9.1 GJ per hectare and 21.1 MJ per kilogram milk solids. Moreover, he recognized that supplementary feeds played a vital role in total energy consumption because of the whole year milk production nature of town milk supply farms and higher milk prices incentives for winter milk. However, due to limited time and the early nature of energy studies in New Zealand, this study has several data collection limitations and then was not followed up with a national survey.

With respect to energy consumption, one of the leading energy studies in New Zealand dairy farming was conducted by Wells (2001), with the help of the Ministry of Agriculture and Forestry (MAF) department. For the first time, Wells (2001) introduced a methodology for the measurement of energy indicators such as production intensity, energy intensity and overall energy ratio (OER) for dairy farms in order to make a baseline for energy analysis of the agriculture sector of New Zealand. Wells (2001) set the system boundary at cradle to farm gate level and considered total primary energy as direct, indirect and capital energy inputs along with a proportion of renewable energy usage. The data were collected from 150 dairy farms across different regions of New Zealand. The findings of the Wells (2001) study highlighted that the value of energy consumption varied from farm to farm depending upon the amount of energy inputs consumed. Moreover, Canterbury farms were identified as the highest energy consumers, whereas Northland farms were found to be the lowest energy users. Further, he revealed that the majority of the NZ dairy industry was reliant on non-renewable energy sources (such as oil, diesel etc.) instead of renewable energy which only accounted for 15% of total energy consumption on farms at that time. He also foretold that farms having the same milk production did not necessarily have the same energy inputs, as different farms have different energy intensities. Further, he identified the factors such as irrigation and fertilizer as most important areas for on-farm energy improvement. Lastly, Wells (2001) recommended that energy indicators should be considered in energy monitoring processes for sustainability of NZ agricultural sectors as they help to maintain annual energy monitoring and overall energy ratios data for New Zealand sustainability.

Afterward, Saunders and Barber (2007) conducted a comparative study on energy and greenhouse gas emissions of New Zealand's and UK's Dairy Industry in response to "Food Miles[1]" debates. Saunders and Barber (2007) followed the same methodology developed by Wells (2001), but with addition of transport distance or shipping cost from NZ to UK. The results of Saunders and Barber (2007) research showed that NZ dairies were more energy efficient than UK dairies. They acknowledged that the UK consumes twice as much energy compared to NZ based on per tonne of milk solids, even including the energy associated with transport from NZ to the UK. This reveals that NZ has a less intensive production system than UK, with lower energy inputs. Regarding GHG emissions, Saunders and Barber (2007) found that the UK dairy production had 34% more emissions per kilogram of milk solids and 30% more per hectare than NZ dairy production even including the shipping to the UK. However, compared to previous studies, Saunders and Barber (2007) did not perform any survey for primary data collection and just used secondary data for NZ national average dairy farms from Wells (2001) study.

In comparison to previous energy studies, Latham (2010) tried to compare energy intensity and greenhouse gas emission of a Canterbury dairy farm with two intensified farms from the McKenzie district, but due to inaccessibility of data for McKenzie district farms, the analysis was restricted to the Canterbury dairy farm only. For this study, Latham (2010) developed a Canterbury model farm through the Ministry of Agriculture and Fisheries (MAF) pastoral modelling programme. Subsequently, Latham (2010) used data from previous research studies (Saunders & Barber, 2007; Saunders, Barber, & Taylor, 2006) and applied a life cycle analysis approach. In general, Latham (2010) observed high energy intensity and double greenhouse gas emissions values for the Canterbury model farm as compared to Saunders and Barber (2007) national average farm. In Latham (2010) study, the main limitation was misinterpreted data of the dairy season 2001 taken from Saunders

[1] Food Miles debate: An issue has arisen in the United Kingdom (UK) and other European countries over food transportation concerns for the environment, especially greenhouse gas emissions.

et al. (2006) study, but actually the data were the dairy seasons of 1997/98 and 1998/99 taken from Wells (2001) study by Saunders et al. (2006). Moreover, the Latham (2010) findings were inconsistent with previous NZ research, in part due to its different methodological approach and using only one farm (data) as the Canterbury model farm, which would not be truly representative data for all farms within the Canterbury region.

Later on, another energy related study in the New Zealand dairy farming sector was conducted by Podstolski (2015), where he used Dairybase data to measure the total energy inputs of dairy farms across different dairy regions of New Zealand. In other words, this study was a replica of Wells (2001) energy intensity work; where Podstolski (2015) used Wells (2001) energy intensity idea to upgrade energy intensity values of NZ dairy farms across different regions, based on NZ industry Dairybase[2] data. In this study, Podstolski (2015) used data from 134 dairy farms, representing 54 districts of New Zealand. His findings indicate that due to dairy intensification the total energy inputs of NZ dairy farms have increased compared to previous decades. Moreover, compared to other regions, Canterbury farms were identified as the highest energy consuming farms across New Zealand.

Although a number of research studies have estimated energy use in New Zealand dairy farming systems, all are based on only the NZ pastoral dairy farming system (PDFs) and there is no consideration of barn dairy farming systems (BDFs). Compared to the pastoral (PDFs) system, the barn (BDFs) dairy system is recently introduced in New Zealand and its number is rising day-by-day due to environmental, animal welfare and soil structure issues. Under this situation, there is a need for a research study, which evaluates NZ contrasting dairy systems based on their energy use and associated carbon emissions in order to identify the more sustainable dairy farming system for the future of the New Zealand dairy industry.

[2] Dairybase collects New Zealand dairy farms data for the recently completed dairy season, through several sources such as survey questionnaires used for farm physical and environmental data collection, while financial data are taken directly from farm accounts or accountants.

1.3.1 Energy Analysis Methods

The agricultural energy analysis includes the identification, estimation and analysis of energy use in farming systems (Fluck & Baird, 1980). Initially, the energy analysis research began as a new subject in agricultural production after the first oil shock in the 1970's. The International Federation of Institutes for Advanced Study (IFIAS) defined the energy analysis as the "determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions" (Slesser, 1974). Consequently, improving agricultural methods and finding new energy resources were noted as important to reducing dependency on fossil fuel energy resources (Fluck & Baird, 1980; Kitani & Jungbluth, 1999; Stout, 2012).

According to Kitani and Jungbluth (1999), in the first step of energy analysis, the energy inputs and energy outputs should be identified and evaluated. Since the energy analysis method was established, the several methods have been used to determine and analyse the energy use in agricultural farming systems. These studies mainly comprise of three methods: statistical analysis, input-output analysis, and process analysis (Safa, 2011). The concept of energy use in agricultural system indicated utilization of energy inputs either direct or indirect such as fuel, electricity, fertilizer, machinery etc. to produce output such as milk or meat. Over the last years, energy consumption in livestock or dairy farming systems got more attention over other agricultural systems due to their high energy requirement for milk production and animal feed preparation (Soltanali, Emadi, Rohani, Khojastehpour, & Nikkhah, 2016).

For estimation of energy consumption in dairy farming systems several methods have been used in past studies. For instance, Vinten-Johansen, Lanyon, and Stephenson (1990) used linear programming method for estimating the energy consumption of 50-ha dairy farm in Pennsylvania, USA and recommended usage of farm energy consumption plan. In another study, the Upton et al. (2013) used life cycle assessment (LCA) approach to determine the electricity consumption of Irish milk production systems during dynamic electricity pricing systems and therefore developed a model for measuring electricity consumption on Irish farms. However, in Upton et al. (2013) study there were no consideration given to other on-farm energy inputs (fuel, fertilizer, feed etc) because of his main study purpose and focus was limited to farm electricity consumption. Likewise, in another study LCA approach for used for measuring the energy use and related environmental impacts of milk production systems (Todde, Murgia, Caria, & Pazzona, 2018a). The LCA approach defined as the four steps approach (i) goal and scope, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation, used as important tool to evaluate environmental impacts associated with production of goods or product with cradle to grave system boundary (Hellweg, 2005). In LCA, cradle refers to the resource extraction phase while grave indicate the disposal phase of product. However, the main challenge in application of LCA approach needed full inventory data from cradle to grave stage to assess environmental impacts of product. In some other studies such as Sefeedpari, Rafiee, Akram, and Komleh (2014) applied adaptive neural-fuzzy inference system (ANFIS) for modelling output energy of dairy farms based on their fossil fuels and electricity consumption. In New Zealand perspective, most of agricultural and dairy energy studies used (cradle-to-gate) energy analysis method to estimate the energy consumption of NZ farms (Podstolski, 2015; Safa, 2011; Saunders & Barber, 2007; Wells, 2001). However, under all international and NZ energy literature the main factors in the selection of any energy method were mainly depend on the nature of data available, study purpose, system boundary, energy coefficients and inputs considered (direct, indirect) etc.

However, for estimating energy related carbon emissions in agricultural systems, most studies used carbon emission coefficient method i.e. where similar to energy analysis method, carbon emissions equivalents used for selected inputs to estimate total carbon emissions of agricultural system. For example, in New Zealand, many agricultural energy studies estimated energy related carbon emissions through this method e.g. meaning they used farm inputs specific carbon emission equivalents to estimate total carbon emissions (Safa & Samarasinghe, 2012; Saunders & Barber, 2007; Wells, 2001). In similar way, in NZ dairy energy literature Wells (2001) and Saunders and Barber (2007) used this method for measuring energy related carbon emissions of NZ pastoral dairy farms. In contrast to this method, the number of international studies used LCA method to assess the energy carbon emissions of agricultural production systems (Todde et al., 2018a, 2018b). Similar to these LCA studies, in NZ Latham (2010) tried to estimate the energy related carbon emissions of NZ dairy farm through life cycle assessment approach, but in actual that study was also based on same approach used by previous NZ energy studies (Saunders & Barber, 2007;

Wells, 2001) instead of following true LCA approach. As the selection of method primarily depends upon the nature of available data. Therefore, based on this study objective and nature of available data, the carbon emission coefficient method was used in this current study.

In literature, the energy efficiency refers to using less energy to produce the same amount of useful output (Patterson, 1996). Useful output of a process can be an energy output, a physical product, or a service (Patterson, 1996). To quantify the energy efficiency, different indicators, such as energy output/input ratio, energy productivity, energy intensity and net energy yield, have been defined and frequently used by previous agricultural energy studies (Hosseinzadeh-Bandbafha et al., 2018; Kuesters & Lammel, 1999; Maysami, 2014). The term energy output/input ratio (OIR) defined as the ratio of usable energy output to final energy input in a system. This indicator is the most famous and common indicator in energy efficiency analysis. Hence, this ratio indicates energy efficiency and widely used in agricultural energy research. In this perspective, several methods have been used in previous studies for estimation of energy efficiency of agricultural farming systems. For example, Meul, Nevens, Reheul, and Hofman (2007) evaluated energy efficiency of specialized dairy, arable and pig farms through process analysis approach. Likewise, in another study energy efficiency of different dairy housing structures used for milk production and animal breeding was assessed by Uzal (2013) through energy analysis approach. Moreover, some other studies used data envelopment analysis (DEA) approach to evaluate energy efficiency of dairy farming systems (Hosseinzadeh-Bandbafha et al., 2018; Soltanali et al., 2016). And this DEA approach become quite famous among researchers and have extensively used for evaluation of energy efficiency of agricultural systems. Thus, based on this study objectives, the DEA was used for evaluation and estimation of energy efficiency, benchmarking and optimal energy consumption of NZ dairy farms selected in this study.

Since, different cropping patterns and energy consumed in agricultural farming systems are very complex systems. They are affected by several factors such as weather, soil physicochemical factors, management conditions, pests, diseases, weeds, field size, degree of mechanization, livestock production etc. Therefore, the selection of suitable method for analysing agricultural energy use depends upon several factors. Moreover, the results of energy studies highly dependent on the set of assumptions used such as defining outputs and inputs, and the energy equivalent of inputs (Conforti & Giampietro, 1997), thus, it needs to be pointed out that local results may not be representative of other areas (Liu, 2009). Thus, comparison and evaluation of results with previous energy studies are difficult. For example, some studies only considered direct or indirect energy inputs (Todde et al., 2018a, 2018b; Upton et al., 2013), while others considered combinations of both direct and indirect inputs (Saunders & Barber, 2007; Wells, 2001). Under these circumstances, a general international agreement on how to estimate energy consumption has been difficult to achieve.

In addition to that, the other most important issues in energy analysis is the non-homogeneity of different sources and the different norms and coefficients that have been used in different studies (Fluck & Baird, 1980). For example, the same amount of fertilizer can have a different energetic cost depending on the technical level of the manufacturing industry. Energy contents depends on the distance of transportation, which is variable, but can be taken as an average value for a region (Kitani & Jungbluth, 1999), similarly, two different fuels might have the same energy content; while, they have different attributes (Fluck & Baird, 1980). There are also problems with energy assignment in the case of multiple outputs, when there is more than one output from a system. In this instance, it is difficult to divide the energy inputs from the outputs. For example, it is impossible to separate the energy needed for grain production from that needed for straw (Conforti & Giampietro, 1997; Fluck & Baird, 1980). Because of these problems, it is difficult to compare one set of data with other published assessments of energy consumption in agriculture across different countries.

Under these situations, through careful consideration and evaluation of all these factors, the energy analysis method was chosen for this study. Because based on this study objectives, the nature of available data, the energy analysis method was the best method to achieve the study objectives.

1.4 Research Gap

The synopsis of dairy energy studies in New Zealand has shown that in spite of the number of energy studies on NZ dairy farming, there has been hardly any study in the literature which compares and evaluates NZ contrasting dairy systems, especially pastoral (PDFs) versus barn (BDFs) dairy systems, in terms of their energy consumption.

At present, the dairy intensification, higher energy usage and related environmental impacts along with other greenhouse gas emissions have raised sustainability challenges for NZ dairy farming systems. Moreover, currently reducing greenhouse gas emissions from NZ dairy farming systems is a critical challenge for the NZ dairy industry. Given the Paris Accord agreement, New Zealand has committed to reduce its greenhouse gas emissions up to 30% below 2005 levels by 2030 (Ministry for the Environment, 2019). Consequently, recently New Zealand's government proposed a "Zero Carbon Bill" which sets new emissions reduction targets for whole NZ industries including the dairy sector, so that carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions have to reduce to net zero by 2050 (DairyNZ, 2019), ultimately causing more pressure on NZ dairy farming systems. Under this situation, a research study on the identification of dairy farming systems with efficient energy consumption along with minimum carbon footprints would help in part to achieve NZ emission reduction targets and reach future sustainable dairy systems. In this context, again NZ literature is very thin and lacking in this kind of research studies. Hence, a study based on carbon footprint evaluation of NZ contrasting dairy systems is necessary for the New Zealand dairy industry.

Similarly, there is not a single study in New Zealand literature, which evaluates energy efficiency of NZ contrasting dairy systems through a data envelopment analysis (DEA) approach. In other words, energy research in New Zealand dairy farming is an area that is still under-studied (especially related to contrasting dairy systems). Thus, there is a clear research gap in NZ literature regarding energy and carbon emissions analysis of contrasting NZ dairy systems. Therefore, there is a need of research study which evaluates energy consumption, related greenhouse gas emissions (CO_2) and energy efficiencies of NZ pastoral (PDFs) and barn (BDFs) dairy farming systems in order to identify energy efficient and environmental sustainable dairy farming systems for the future of the New Zealand dairy industry.

1.5 Research Objectives

The limited energy resources along with rising energy costs and environmental concerns are causing sustainability challenges for dairy farming systems. Currently, dairy farming systems use more energy compared to other agricultural production systems (Pressman, 2010). Therefore, knowledge related to energy management is necessary in order to conserve energy and minimize environmental impacts of dairy farming systems.

Previously, the number of research studies have estimated the energy use of the NZ pastoral (PDFs) dairy system, but there is no study on the barn dairy farming system (BDFs) in terms of energy consumption. Therefore, the researcher of this thesis strongly believes that the energy consumption in NZ contrasting dairy systems must be investigated in order to control and save energy along with reducing environmental impacts of NZ dairy farming systems. Further, investigation of energy efficiencies and associated carbon emissions of NZ contrasting dairy systems would help in identifying energy efficient and environmental sustainable dairy systems for the future of the NZ dairy industry.

Therefore, the first objective of this study was to estimate the energy consumption of NZ pastoral (PDFs) and barn (BDFs) dairy farming systems in Canterbury. For better understanding, energy consumption in both dairy systems was estimated based on their land use area and milk production basis.

The second objective of this study was to assess energy related carbon emissions of both pastoral (PDFs) and barn (BDFs) dairy farming systems, from a comparative perspective. This objective would help to understand and provide a clear picture about how much energy related carbon dioxide (CO_2) emission is produced in each type of dairy system, both on a per hectare and milk production basis.

The third objective of this study was to evaluate the energy efficiency of both dairy systems (PDFs and BDFs), through the data envelopment analysis (DEA) technique. This energy efficiencies comparison between dairy systems would help to understand how efficiently farmers using their energy inputs on farms. Further, benchmarking was performed to separate the efficient farms from inefficient ones and also energy saving potential was identified in both dairy systems through their optimal energy consumption estimation.

In summary, the main objectives of this study were as follows:

- To estimate and compare the energy consumption in pastoral and barn dairy systems.
- To estimate and compare the energy carbon footprints of pastoral and barn dairy systems.
- To estimate and compare the energy efficiency of pastoral and barn dairy systems.

1.6 Research Methods

For measuring the energy consumption and related environmental emissions in dairy farming systems, it is essential to provide a clear picture of the study region along with information about the energy inputs and method used to gather the data. The main aim of this study was to evaluate and compare New Zealand contrasting dairy systems (PDFs and BDFs) in terms of their energy use, efficiency and related environmental emissions (CO_2). So in this study, the Canterbury region is selected as a case study. Canterbury is one the largest regions in New Zealand, with total land area of 45,346 square kilometres (Statistics New Zealand, 1999), and has the second highest population in New Zealand with 539,436 people (Statistics New Zealand, 2013). About 19% of NZ's total dairy cows are in Canterbury (905,076 cows) with an average herd size around 764 cows (DairyNZ, 2017b). Canterbury is also one of the important and influential regions of New Zealand, with total dairying in the region valued at around NZ$2.3 billion in 2016-17 (DairyNZ, 2017b).

In this study, an energy analysis method was employed to measure the energy consumption in New Zealand pastoral (PDFs) and barn (BDFs) dairy farming systems. The energy analysis method used engineering techniques to measure and forecast energy consumption and energy efficiency in different fields (Randolph & Masters, 2008). For estimating the energy consumption and related carbon emissions of dairy farms, the data related to farm inputs (direct & indirect) involved in the production of milk until it leaves the farm gate were considered. In other words, the data related to farm inputs such as diesel, petrol, electricity, human labour, fertilizers, imported feed supplements and machinery involved in the production of milk were needed to measure the energy consumption and related carbon emissions. In this study, this information was collected through a survey questionnaire from both types of dairy farms (pastoral and barn). Further, to measure the total energy consumption and related carbon emissions of dairy farms, the farm inputs data were converted into energy and carbon emissions units through multiplying their corresponding energy and emissions conversion coefficients selected after careful investigation of different studies (detailed methods discussed in Chapters 2 and 3).

Further, to measure and compare the energy efficiency of selected dairy farms, data envelopment analysis (DEA) technique was employed in this study. DEA has become very popular among researchers due to its ability to compare the relative energy efficiency of agricultural production systems including dairy systems (Hosseinzadeh-Bandbafha et al., 2018; Omid, Ghojabeige, Delshad, & Ahmadi, 2011).

1.6.1 Data Collection

Data collection was a critical part of this study. In this study, the data were gathered through survey questionnaire and face-to-face interviews with pastoral and barn dairy farmers. The following sections explained the data collection process, including designing a survey questionnaire and finding the potential participants or farmers.

1.6.2 Survey Questionnaire Structure

To find the total energy inputs for each farm, there is a need to design a flexible and practical survey questionnaire. In this study, the survey questionnaire comprised several sections with specific aims and each section was designed to collect precise data rapidly but comprehensively. The survey questionnaire has been approved by the Lincoln University Human Ethics Committee (See Appendix A.1).

The survey questionnaire was developed based on prior research examining energy use in the New Zealand agriculture sector including the dairy industry (McChesney, 1979; Safa, 2011; Wells, 2001). For this survey, the farmers' responses were obtained through face to face interviews conducted in the year 2017/18 (as face to face interview and mailing methods were tested and it was found that face to face interview were the best method to carry out the survey). The initial developed questionnaire was improved step by step through meetings with farmers (pilot study), and consultation with scientists from Lincoln

University, DairyNZ and some other people from NZ dairy industry institutions. Before data collection, the survey questionnaire was pre-tested by ten randomly selected farmers from Canterbury and these pre-tested surveys (pilot study) were not included in the final data set. The questionnaire included questions about farm inputs and output related to milk production and included a research information sheet (Appendix A.2) explaining the purpose of the survey and gave some brief information about energy and benefits of this study for the New Zealand dairy industry. The research information sheet also contained some information and contact details of the researcher of this project.

The questionnaire was divided into nine main sections (See Appendix A.3); 1. Farm system information (This part of the questionnaire was designed to get information about the farm system according to DairyNZ system classification, type and time usage of barn structure), 2. Information about farm area (This part of the questionnaire asked questions about total farm land with its subsequent usage for milking platform, milking shed etc.), 3. Livestock information (This part covered the information about type and number of dairy cattle including their age and weight etc.), 4. Milk production (This section provides information about annual milk production for each farm along with proportions of their milk ingredients), 5. Machinery usage (This part of the questionnaire gives the information about number and time usage of machinery such as tractors, utes, bikes etc., along with power and age of machinery), 6. Milking parlour (This part of the questionnaire was designed to get information about milking shed equipment such as Herringbone, Rotary etc. and their number of cups), 7. Direct energy inputs (This portion of the questionnaire asked information about direct energy inputs such as diesel, petrol, electricity, labor etc. involved during the whole dairy season), 8. Feed consumption (This section covers the information about feed usage for each farm), 9. Fertilizer usage (This section provides data for fertilizer consumption in each farm).

1.6.3 Survey Distribution

In this study, the potential survey participants were pastoral (PDFs) and barn (BDFs) dairy farmers from Canterbury, New Zealand. The survey was performed for the dairy season 2016-17 data. Prior to the main data collection, the pilot study was conducted using 10 dairy farmers from Canterbury, to pre-test the survey questionnaire and number of options[3] were added, removed or changed in order to develop a questionnaire which was easy to understand and answerable by farmers. The main survey was carried out between June 2017 and May 2018 and the farmers (potential respondents) were contacted through Lincoln University (professors) and some dairy industry companies such as DairyNZ, Fonterra etc. Some farmers were approached through making contacts on NZ dairy events such as SIDE conference 2017, dairy barn conference 2017 (organised by the Centre for Dairy Excellence) etc. Further, snowball sampling methods (where a respondent may pass the survey to other related respondents) were used to obtain more farmers or respondents. For data collection interviews, appointments were made with farmers through phone calls and interview times ranged between 2-3 hours.

According to DairyNZ (2017b), there were total 1184 dairy farms in Canterbury during the 2016-17 dairy season, out of which around 30 to 35 farms were using barn facilities[4]. Regarding sample size for this study, finding 100 samples was the initial target. But due to time limits, sample size was restricted to 50 dairy farms only, including 43 pastoral farms (4% representative data of Canterbury pastoral farms) and 7 barn farms (approximately 20% representative data of Canterbury barn farms).

1.6.4 Data Analysis

For data analysis and to convert the different quantitative data of the survey questionnaire into energy and carbon units, it was necessary to establish effective spreadsheets. For this purpose, the number of spreadsheets were developed in Microsoft Excel. Data were entered manually into a Microsoft Excel spreadsheet and checked multiple times to remove any data entry error. The final estimations were calculated by entering conversion coefficients, formulae and equations in the spreadsheet. And the main spreadsheets contained all required energy and emission coefficients and were used to estimate energy use and carbon emissions for each farm.

[3] In pilot study, author tried to collect detail electricity, medicines and buildings (barns, sheds etc. buildings data to find embodied energy of buildings) data, but it was not feasible to get that information from farmers. So excluded from main survey.

[4] Personal Communication with DairyNZ staff, as the author is also assisting or working for DairyNZ as Dairybase 'Data Collector' for Canterbury region.

Further, to measure the energy efficiencies of dairy farms the study developed a frontier efficiency model, which estimates the relative efficiency based on milk production in comparison to the efficienct (best) dairy farm in the sample. In this way, only the efficienct (best) dairy farm lies on the frontier. For this purpose, the data envelopment analysis (DEA) was employed using DEAP software (version 2.1), as this approach does not require any prior functional form specification between the inputs and outputs and mostly suitable for benchmarking (Coelli, 1996; Coelli, Rao, O'Donnell, & Battese, 2005). In this study, the dairy farms are the decision-making units (DMUs) whereas farm energy inputs and milk energy were considered as inputs and output, respectively. The DEA model is explained in detail in chapter 4 section 2.2.

1.7 Chapters Overview

This thesis consists of five chapters, including a general introduction, three journal paper articles focussed on the three specific objectives and an overall conclusions chapter.

Chapter 1: This chapter provides a general introduction of the study and dairy farming systems in New Zealand. This chapter also highlights the history of energy studies in NZ dairy farming and identifies the energy issues and knowledge gap in the literature. The specific research objectives, methods used, and the chapter's overview are also presented at the end of this chapter.

Chapter 2 **Manuscript 1: Evaluation of the Energy Consumption of Pastoral and Barn Dairy Farming Systems in New Zealand:** This chapter explains the measurement of the energy consumption in New Zealand pastoral (PDFs) and barn (BDFs) dairy farming systems based on direct and indirect energy inputs. Further, this chapter classifies the total energy consumption of both dairy systems into different energy sources. Finally, a multiple linear regression model was developed for the prediction of energy consumption in New Zealand dairy farming systems. Findings of chapter 2 address objective 1.

Chapter 3 **Manuscript 2: The Carbon Footprint of Energy Consumption in Pastoral and Barn Dairy Farming Systems: A Case Study from Canterbury, New Zealand:** This chapter identified energy related carbon footprints (CO_2) of both PDFs and BDFs dairy systems of New Zealand. To predict carbon footprints in NZ dairy systems, chapter 3 developed a carbon emission prediction model. The results of this study addressed objective 2 and identified potential mitigation options for reducing energy related carbon emissions in both dairy systems of New Zealand.

Chapter 4 **Manuscript 3: Energy Efficiency Outlook of New Zealand Dairy Farming Systems: An Application of a Data Envelopment Analysis (DEA) Approach:** This chapter explains the comparison of the energy efficiency of NZ contrasting dairy systems to identify energy efficient dairy systems. In addition to that, chapter 4 performed benchmarking on selected dairy farms, in order to separate the efficient farms from inefficient ones. In the end, energy saving potential was identified for both type of dairy systems through their optimal energy consumption estimations. The outcome of chapter 4 addresses objective 3.

Chapter 5 draws overall conclusions from the preceding chapters. Then, based on the overall study some suggestions for on-farm energy improvement and potential mitigation options for reduction in energy related carbon footprints in NZ dairy farming systems are summarized. Lastly, a critical evaluation of the methods used in this study is developed and recommendations for future research work are highlighted.

Chapter 2

Evaluation of the Energy Consumption of Pastoral and Barn Dairy Farming Systems in New Zealand[5]

Abstract

Energy consumption is an important component in determining the sustainability of farming practices. Identification of dairy farming systems with efficient energy consumption at the same time as minimising greenhouse gas emissions is vital. In this context, it is relevant to assess the energy consumption of different dairy farming systems in order to identify a sustainable dairy system for the future of the NZ dairy industry. This research is based on a comparative analysis of Pastoral (PDFs) and Barn (BDFs) dairy farming systems in Canterbury, New Zealand. A total of 50 dairy farms were investigated, using direct (fossil fuel, electricity, labour) and indirect (fertilizer, imported feed supplements, machinery) energy inputs.

The findings of this study indicate that total energy consumption of pastoral (PDFs) and barn (BDFs) dairy systems were found as 50538 MJha^{-1} and 55833 MJ ha^{-1} respectively. Among total energy consumption, electricity (35.5%) and fertilizer (29.9%) were the main energy inputs in PDFs, while in BDFs, electricity (34.8%) and imported feed supplements (24.1%) were the leading energy inputs. From a system comparative perspective, the results indicate that pastoral (PDFs) system have 9.5% lower energy consumption per hectare than the barn system (BDFs), mainly due to their greater reliance on pasture based grazing feeding and less use of electricity, fuel and imported feed supplements. In terms of per kilogram milk solids produced, the PDFs shows 6% less energy consumption compared to BDFs. Thus, this research suggests that energy consumption in PDFs in terms of both hectare and milk output is more efficient.

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[5] This chapter has been published in the 22nd International Farm Management Association (IFMA) Congress proceedings, held in Tasmania, Australia on 3-8 March 2019 (Ilyas, Safa, Bailey, Rauf, & Cullen, 2019). The main work was conducted by Hafiz such as concepts development, data collection & analysis and write-up of the manuscript. All co-authors provided assistance and feedback on development of the manuscript. (See Appendix B.1).

Keywords: Energy Consumption, Pastoral Dairy Farming System (PDFs), Barn Dairy Farming System (BDFs)**,** Canterbury' New Zealand

2.1 Introduction

Energy is a critical input and significant cost for dairy farming systems. Energy consumption in dairy farming systems comprises both renewable and non-renewable energy resources. It consumes large quantities of energy inputs such as diesel, electricity, fertilizer, irrigation water and machinery. Where there is efficient use of these energies, this can help to increase productivity and profitability along with reductions in environmental emissions and cost associated with milk production (Singh et al., 2002; Todde et al., 2018b). Among these energy inputs, fossil energy is one of the important energy inputs involved in dairy farming operations evident in feed production, transportation, storage, processing and distribution. Depending on the farming system, weather condition and building facilities, energy is also needed for cooling, heating or ventilation purposes in order to control the thermal environment; this may also include for livestock waste management (Frorip et al., 2012). However, fossil fuel energy resources are becoming increasingly limited, so it is essential to replace fuel energy with new or renewable energy sources or otherwise optimize consumption of existing resources to manage future energy demand. Consequently, it is necessary to recognize the different input elements in farming systems and promote the methods to control them (Safa, Samarasinghe, & Mohssen, 2011).

Dairying is one of New Zealand's largest agricultural sectors, with 4.8 million dairy cows on 11,748 dairy farms producing over 21 billion litres of milk (1.8 billion kg MS) per year (DairyNZ & LIC, 2017a). Canterbury is one of the most important and influential regions of New Zealand, with dairying in the region valued around NZ$2.3 billion in 2016-17. About 19% of NZ's total dairy cows are in Canterbury (905,076 cows) with an average herd size around 764 (DairyNZ, 2017b). Over the last decades, the NZ dairy industry has significantly expanded in Canterbury in both land area farmed and number of cows milked. According to a Statistics New Zealand (2018) report, the numbers of dairy cows are constantly rising in the Canterbury region compared to overall New Zealand dairy cattle numbers which have stabilized since 2012. The reason for this intensification and expansion of the Canterbury dairy industry was the development of irrigation and subsequent rapid conversion of mixed dryland livestock and cropping farms into dairying as a result of higher profitability in the dairy sector (Pangborn, 2012). As consequence of dairy intensification, energy consumption per hectare of land or per kilogram of milk solids has increased along with a rising stocking rate (Podstolski, 2015). Due to growing on-farm energy consumption along with the rising energy cost and environmental concerns, an understanding of energy consumption is becoming more important for farmers. Hence, the need for an evaluation of energy consumption of farming systems, to compare the energy cost of existing process operations with that of new or modified production operations is essential (Kythreotou, Florides, & Tassou, 2012).

Several studies have assessed the energy consumption of the dairy farming sector both worldwide and in New Zealand. For example; Austin (2012) determined the energy use in Australian dairy farms comparing organic and conventional dairy systems and found that organic dairies were 22-28% more energy efficient than conventional dairies depending upon farm sizes. Likewise in the European Union, Meul et al. (2007) performed energy analysis on Flanders dairy farms and found that fertilizers and animal feed contributed to a maximum indirect share in energy consumption, whereas diesel was the highest input among the direct energy sources. Moreover in Ireland, on average 31.73 MJ of energy was consumed to produce one kilogram of milk solids, of which direct and indirect inputs accounted for 20% and 80% of total energy consumption respectively (Upton et al., 2013).

However, in New Zealand the energy inputs of dairy farming has been measured by a number of researchers (McChesney, 1979; Podstolski, 2015; Saunders & Barber, 2007; Wells, 2001). For example, McChesney (1979) initially performed a survey of twelve town milk supply farms in Canterbury in order to measure energy inputs for the New Zealand dairy farming sector and found total energy inputs as 9100 mega joules per hectare with irrigation as the most energy consuming event. Then, Wells (2001) developed energy indicators based on energy use of NZ dairy farms in order to determine the sustainable agricultural practices. In another study, Sim, Jayamah, Barrie, Hartman, and Berndt (2004) analysed electricity consumption in milking sheds of dairy farms, but without considering other direct (petrol, diesel) and indirect (fertilizer, feed supplements) energy inputs. Later on, Saunders and Barber (2007) compared NZ and UK dairy industries based on energy consumption and found the NZ dairy industry had lower energy consumption than the UK industry. In another study, Barber (2008) measured energy use for a Lincoln University dairy farm through a life cycle assessment (LCA) approach and found lower energy use in the Lincoln University dairy farm compared to a typical NZ dairy farm, based on milk production. Subsequently, Latham (2010) tried to compare the energy use of a Canterbury dairy farm with two intensified farms from the McKenzie district, but due to inaccessibility of data, his analysis was restricted to a Canterbury dairy farm only. Afterwards, similarly to Wells (2001) study, the Podstolski (2015) study measured total energy inputs for the NZ dairy industry based on different regions.

However, all of these NZ studies were just focused on agrass-based pastoral dairy system and there was no consideration of the barn dairy system. The barn is a relatively new system introduced in NZ as consequences of animal welfare and environmental concerns (Pow et al., 2014). In spite of the large investment needed in a barn system, it has a number of perceived benefits such as better control of animal feed and health, better effluent management, and less soil and pasture damage during wet conditions (Longhurst, Miller, Williams, & Lambourne, 2006). Alongside the financial, welfare and environmental management implications that are perceived, it is also important to evaluate both systems in terms of their energy consumption in order to identify a sustainable dairy farming system for the future of the NZ dairy industry. Therefore, the aim of this study was to determine the energy consumption of pastoral (PDFs) and barn (BDFs) dairy systems from a comparative perspective, based on a hectare and milk production basis. Further, different energy sources involved in both dairy systems were also identified.

2.2 Materials and Methods

This study was based on data from 50 dairy farms located in the Canterbury province, New Zealand. The data were collected using two different approaches: questionnaire and literature review.

The following two dairy farming systems were studied:

i. Pastoral Dairy Farming System (PDFs): the typical New Zealand system where animals are kept on pasture year-around through rotationally grazed irrigated paddocks.
ii. Barn Dairy Farming System (BDFs): In addition to pasture grazing, animals are housed in barn buildings such as Freestall, Herdhomes etc. for different time durations during the season, named the "Barn Dairy Farming System".

2.2.1 System Boundaries and Functional Units

The methodology used for this study is “cradle-to-gate” analysis, which means transportation and post-processing components of the milk production life cycle are excluded after they leave the farm gate (as shown in Figure 2-1). All information on direct and indirect energy inputs was collected through a survey questionnaire and face-to-face interview with farmers. For this study, 50 dairy farms including pastoral (43) and barn (7) were selected. The information gathered through the survey questionnaire included type of farming system, total land area, livestock numbers, milk production, type of machinery and time usage, milking equipment, human labour, quantity of diesel, petrol, electricity, amount of fertilizer and feed supplements. From a comprehensive literature review, the equivalent energy inputs were determined for all inputs and output parameters. Hence, the total primary energy consumption of pastoral (PDFs) and barn (BDFs) dairy farming systems was determined through a combination of direct and indirect energy inputs. The detailed methods for estimation of energy coefficients and calculations of direct and indirect energy inputs are described in the following sections.

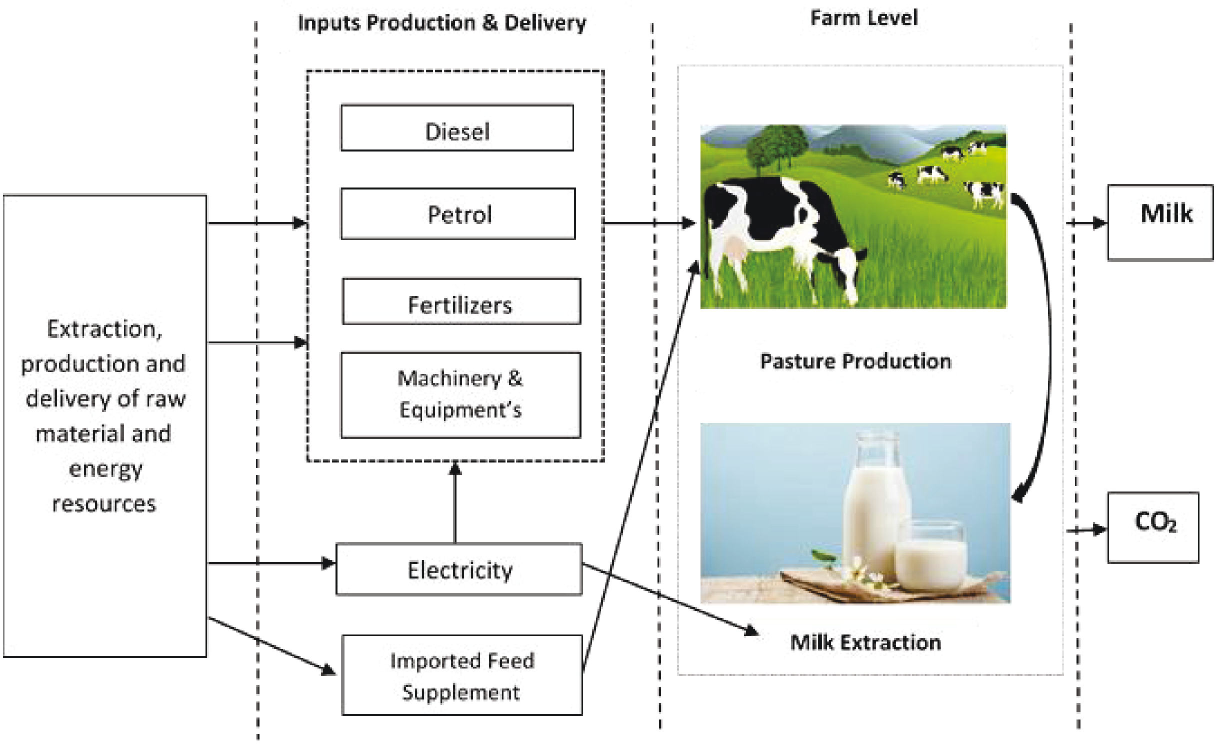

Figure 2 - 1: "Cradle to gate" System Boundaries for PDFs and BDFs Dairy Systems

2.3 Energy Inputs Parameters

Energy inputs into a dairy farming system can be categorized as direct and indirect uses of energy (Uzal, 2013). Direct use of energy included energy inputs which are directly involved in the production process of farming systems and included energy derived from diesel, petrol, electricity, human labour. Whereas, indirect use of energy comprised energy inputs from material consumed; such as farm machinery and feedstock (maize silage, grass silage, concentrates etc.) used in dairy production systems (Heidari, Omid, & Akram, 2011; Meul et al., 2007; Mohtasebi, Mehroozi Lar, Safa, & Chaichi, 2008).

In the present study, direct energy inputs consist of fossil fuels, electricity and human labour inputs. While indirect energy inputs comprise fertilizer, imported feed supplements and farm machinery. From the literature, the values for energy coefficients were selected and

Table 2 - 1: Energy Equivalents for Inputs used in PDFs and BDFs Dairy Systems

Inputs items	Unit	Energy Coefficients ($MJ\ unit^{-1}$)	References
Direct Energy Inputs			
Diesel	litres	45	MED (2012)
Petrol	litres	42	MED (2012)
Electricity	kWh	8	MED (2012)
Human Labour	hours	1.96	Mani, Kumar, Panwar, and Kant (2007)
Indirect Energy Inputs			
Fertilizers			
Nitrogen (N)	kg	64.1	Wheeler (2018)
Phosphorous (P)	kg	28.4	Wheeler (2018)
Potassium (K)	kg	17.8	Wheeler (2018)
Sulphur (S)	kg	3.24	Wheeler (2018)
Feed Supplement			
Grass Silage	t DM	1781	Wheeler (2018)
Maize/Cereal Silage	t DM	1564	Wheeler (2018)
Hay	t DM	1329	Wheeler (2018)
Grains	t DM	3905	Wheeler (2018)
Concentrates	t DM	1800	Wheeler (2018)
Machinery & Equipment			
Tractors	kg	160	Wells (2001)
Utes	kg	160	Wells (2001)
2-Wheeler Motorbikes	kg	160	Wells (2001)
Milking Shed	sets of cups	Shed Energy¶	Wells (2001)

¶ $Shed\ energy\ (MJ) = (24.2 * number\ of\ cups + 293) * 1000$

used for estimation of the energy content of each direct and indirect energy input (as shown in Table 2-1).

2.4 Direct Energy Inputs

2.4.1 Fossil Fuel

In agriculture, energy from fuel consumption is of great importance due to its influence on production cost (Nguyen & Haynes, 1995; Safa, Samarasinghe, & Mohssen, 2010). In NZ dairy systems, diesel and petrol are the main fuel inputs used in farm activities for operating farm machinery (tractors, motorbikes, trucks). The primary energy content of diesel and petrol were 45 and 42 MJ per litre respectively, encompassing consumer energy plus energy spent for extraction, processing, refining and transportation (MED, 2012). In this study, the fuel amount consumed during the season including contractor's fuel was estimated through the survey questionnaire, and the primary energy input from fuel calculated by multiplying the fuel amount by the appropriate energy equivalent (Table 2-1).

2.4.2 Electricity

In Canterbury dairy farming systems, the electricity is mainly consumed in irrigation and milking shed operations. In the milking shed, electrical energy is mainly used for water heating, lighting, cooling and milk harvesting purposes. Moreover in Barn systems (BDFs), electricity is also used for lighting, ventilation, cleaning, and operating some barn equipment (animal brushing, effluent scraper etc.).

In New Zealand, electricity is mainly generated through hydro, coal, wind and geothermal energy sources. The basic conversion factor for electricity is 3.6 MJ kWh^{-1}, however this conversion factor does not account for inefficiencies in electricity generation. In New Zealand, the primary energy content of electricity was found to be 8 MJ kWh^{-1} MED (2012). In this study, the total amount of electricity[6] used in PDFs and BDFs systems were determined

[6] Note: The amount of electricity collected through survey questionnaire was comprised of total electricity usage including irrigation, dairy sheds and all other operations etc., as it was hard for farmers to provide separate or in detail electricity data for each farming operation.

through the survey questionnaire and then the total electrical energy input was calculated by multiplying the electricity amount by the relevant energy equivalent (Table 2-1).

2.4.3 Human Labour

In agricultural energy analysis, several studies have considered human labour as an important energy input resource with an energy equivalent of 1.96 MJ ha^{-1} (Mani et al., 2007; Ozkan, Akcaoz, & Karadeniz, 2004; Safa et al., 2011). In dairy farming systems, human labour is involved in almost every task on the farm such as driving machinery, repairs and maintenance, feed distribution, milking cows, animal care, fertilizer, irrigation and farm management etc. In this study, the amount of labour input (hours) was obtained through the survey questionnaire and the value for labour energy equivalent was taken as 1.96 MJ ha^{-1} (Mani et al., 2007). Thus, the labour energy was estimated by multiplying the energy coefficient with the total hours of labour involved in different farming activities.

2.5 Indirect Energy Inputs

2.5.1 Fertilizer

In New Zealand, chemical fertilizer is one of the most significant indirect energy inputs used on dairy farms. As a result of dairy intensification, annual use of N fertilizer in New Zealand increased from 59,265 tonnes to 366,600 tonnes from 1990 to 2007 (Ministry for the Environment, 2016). The embodied energy involved in manufacturing each fertilizer component N, P, K, S were considered as 64.1, 28.4, 17.8, 3.24 MJ kg^{-1} respectively (Wheeler, 2018). In this study, fertilizer amount used in both PDFs and BDFs systems was recorded by fertilizer type (urea, DAP, superphosphate). Subsequently, fertilizer energy input associated with each fertilizer type was estimated by breaking down each fertilizer into its essential components (N, P, K, S), and then multiplied by their relevant energy coefficient (Table 2-1).

2.5.2 Imported Feed Supplements

Imported feed supplements have a strong influence on the energy consumption of NZ dairy farming systems. In general, the feed supplements used in dairy farming systems fall under two situations: to combat a feed deficit or for achieving higher milk production per cow.

However, the intensification of the NZ dairy industry and increased stocking rate have resulted in high usage of imported feed supplements in some NZ dairy systems. In New Zealand, the most common types of feed supplements are maize silage, grass silage and hay. In this study, the energy equivalents for grass silage, maize silage and hay were considered as 1781, 1564, 1329 per tonne dry matter (Wheeler, 2018). The amount of imported feed consumed during the season was estimated through survey questionnaire for both PDFs and BDFs, whereas feed was adjusted for PDFs for their winter grazing period. Thus, energy consumption associated with imported feed supplements for both PDFs and BDFs were estimated through multiplying the amount of feed consumed by the relevant energy equivalents (Table 2-1).

2.5.3 Machinery and Equipment

In agriculture, commercial energy is mainly used in the manufacturing operations of farm machinery, which can be classified into energy requirements for manufacturing, repair and maintenance (Conway, 1991; Safa et al., 2011). In New Zealand pastoral and barn dairy systems, farmers used different types of agricultural machinery (tractors, ute, quadbikes etc.).

To estimate the energy input of tractors and other machinery, it is necessary to know the mass (kg), energy equivalent, economic life and working hours of machinery used during the milking season. In this study, the economic life of different machinery was taken from the (ASAE, 2011), the annual use of machinery was estimated through the survey questionnaire, while energy equivalents and average mass of different machinery were considered from (Wells, 2001). Thus, energy consumption for each machinery and equipment was calculated by using equation 2-1 (Uzal, 2013).

$$ME = ms * EE * t/T \tag{2-1}$$

Where ME represents the machinery energy (MJ ha^{-1}), ms is the mass of machinery (kg), EE is the energy equivalent of the machinery (MJ kg^{-1}), t is annual working hours of machinery (hour) and T is the economic life (hour).

According to Wells (2001), the tractors used in NZ farming systems have power ranges between 25 and 400 hp, and there is strong correlation between tractor mass and horse power (hp), hence in this study, the mass of different tractors is estimated through equation 2-2 (Wells, 2001).

$$Mass\ (kg) = 40.8 * Power\ (hp) + 190 \tag{2-2}$$

In New Zealand dairying, the most popular milking parlour types are rotary and herringbone. According to Wells (2001), the embodied energy involved in dairy sheds increases linearly with the number of cups in the milking parlour. Hence energy consumption in dairy sheds of PDFs and BDFs is estimated according to the following equation (2-3); which considered embodied energy required for construction of the dairy sheds including yards, roof, walls, backing gates, floor of milking area, tanker pad, vat stand and milking plant (Wells, 2001):

$$Shed\ energy\ (MJ) = (24.2 * x + 293) * 1000 \tag{2-3}$$

Where *x* = number of cups of the milking parlour

Assumed working life of milking parlours = 20 years

2.6 Energy Prediction Model

Energy modelling is an important concern for scientist and researchers as price volatility and environmental impacts compel farmers to produce at lower prices. For empirical analysis, multiple linear regression (MLR) models had been widely applied within the agricultural domain for energy consumption prediction (Edens, Pordesimo, Wilhelm, & Burns, 2003; Safa & Samarasinghe, 2011; Wells, 2001). Particularly, in dairy related research MLR modelling has been used by researchers for predicting different energy inputs. For instance, in electricity consumption (Edens et al., 2003; Shine, Scully, Upton, Shalloo, & Murphy, 2018; Todde, Murgia, Caria, & Pazzona, 2017), water prediction (Higham, Horne, Singh, Kuhn-Sherlock, & Scarsbrook, 2017; Meyer, Everinghoff, Gädeken, & Flachowsky, 2004; Murphy et al., 2017; Shine et al., 2018) and dairy farm energy requirements (Wells, 2001).

Multiple linear models define the linear relationship between multiple explanatory variables for prediction of a dependent variable (energy consumption), as given in equation (2-4) (Gujarati, 2009; Shine et al., 2018; Todde et al., 2017). For that purpose, the relationships between energy consumption and energy inputs and production indicators were investigated to determine the factors contributing significantly to energy consumption of dairy farms. A univariate variable selection method was employed to select highly correlated variables to energy consumption for linear prediction. Variables significant at less than p = 0.1 were retained in the model (Shine et al., 2018). Furthermore, a binary variable for each dairy system was also included in the model, to determine the impact of different farming systems (PDFs or BDFs). A multiple linear regression model equation (2-4) to predict energy consumption was developed as:

$$EC_i = \alpha_0 + \alpha_1 X_{1i} + \alpha_2 X_{2i} + \ldots\ldots + \alpha_5 X_{5i} \qquad (2\text{-}4)$$

Where:

EC_i = Energy Consumption of the i^{th} dairy farm

i = *1,2,3…….,50 dairy farms*

α_0 =Intercept,

αi = independent variables fixed effects,

X_{1i}= total electricity consumed by the i^{th} dairy farm,

X_{2i}= total nitrogen applied at the i^{th} dairy farm,

X_{3i}= total feed supplements brought in at the i^{th} farm over the year,

X_{4i}= dairy farming system of the i^{th} dairy farm *(Pastoral=1 or Barn=0)*

X_{5i}= number of milking cows at the i^{th} dairy farm and 'ε' the error term.

The model developed contained only the significant and non-correlated variables. Multi-collinearity (correlation between independent variables) exists in cross-sectional data mostly, which can lead to inaccurate model estimation. The Variance Inflation Factor (VIF) test was employed to detect multi-collinearity in the model. Variables with values lower than 10 were used in the model, as they are not affected by multi-collinearity. The model was developed on the randomly selected training data (90 percent) and the model predictions were projected on validation data (10 percent). The multiple linear model goodness to fit for training and validation was also assessed by estimating the root mean square error (RMSE), which expresses how spread the residuals are around the best fitted line (Gujarati, 2009).

2.7 Results

2.7.1 Characteristics of Dairy Farms

The characteristics of both the pastoral (PDFs) and barn (BDFs) dairy systems are summarized in Table 2-2. In terms of effective milking area (effective hectares) and herd size (number of milking cows), variation was observed in both dairy systems. The milking area for pastoral farms varied from 80 to 800 effective hectares with an average of 252, whereas for barn farms it varied from 86 to 560 effective hectares with an average of 232. In the same way, herd size of PDFs ranged between 250 and 3177 milking cows, with an average of 855 while for BDFs it ranged between 240 and 1692, with an average of 846 milking cows. Of interest is that the averaged milking area and herd size were more in PDFs compared to BDFs, but the average stocking rate (cows per effective hectare) for barn farms (3.6) was higher than the pastoral farms (3.4).

Table 2 - 2: Characteristics of Dairy Farms

		Pastoral				Barn			
Particulars	**Units**	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Milking Area	Effective ha	252	151	80	800	232	166	86	560
Herd Size	No. of cows	855	521	250	3177	846	547	240	1692
Stocking Rate	Cows ha^{-1}	3.4	0.5	2.3	4.8	3.6	0.9	2.8	5.5
Milk Solids Production	Tonnes MS	384	217	120	1257	385	234	120	662
	kgMS ha^{-1}	1594	460	860	2477	1687	485	1181	2545
	kgMS cow^{-1}	460	108	250	772	462	42	391	500

Similarly, there was substantial variation amongst the smallest and largest farms of both dairy systems in terms of milk production. The annual milk solids production ranged between 120 and 1257 tonnes for pastoral farms, whereas for barn farms, it ranged between 120 and 662 tonnes of milk solids. Based on per hectare and cow, the average milk solids production was higher in barn farms compared to pastoral farms. However, for pastoral farms, the milk production varied from 860 to 2477 kg of milk solids per hectare and 250 to 772 kg of milk solid per cow, while for barn farms it ranged from 1181 to 2545 kg of milk solids per hectare and 391 to 500 kg of milk solid per cow.

A strong relationship between milk solids production and herd size was found for both the dairy farming systems. Figure 2-2 illustrates that 88 and 96 percent variation in milk solids production is explained by herd size in pastoral and barn dairy farms, respectively. This suggests herd size as the main determinant for milk solids production for both the dairy systems. The amount of milk solids produced in both types of dairy systems increases significantly as the herd size increases advocating more cows means more milk production.

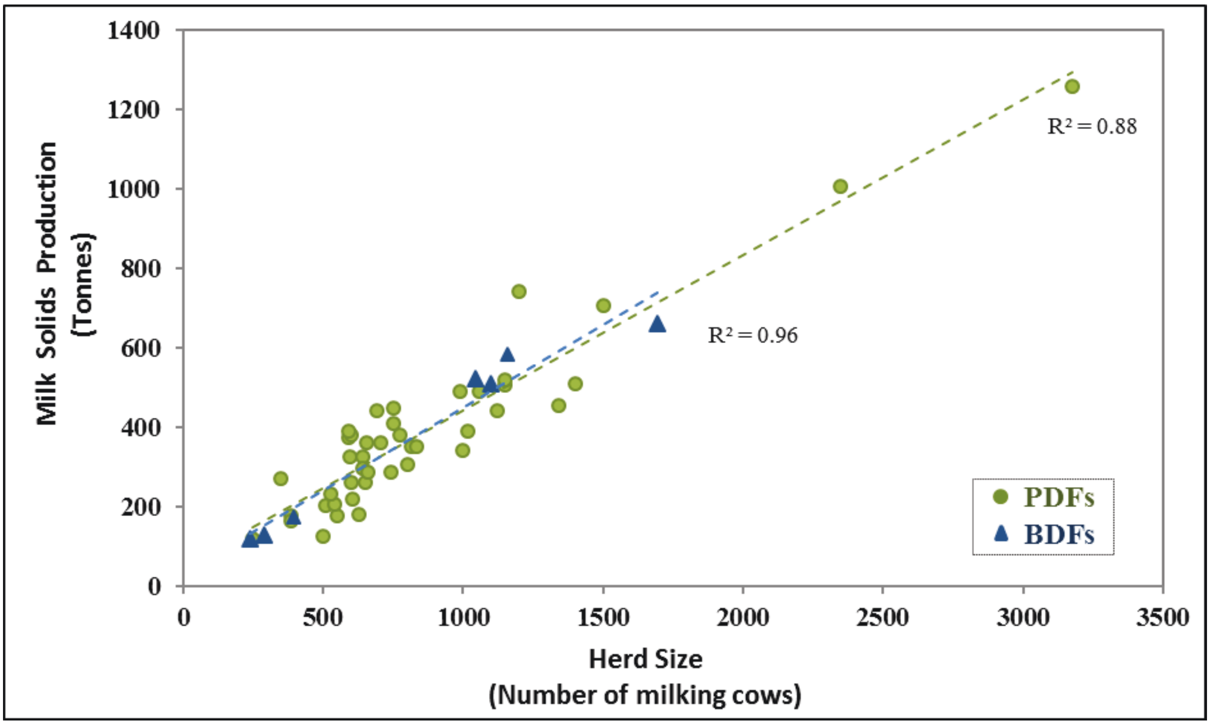

Figure 2 - 2: Relationship between Milk Solids Production and Herd Size

The Figure 2-3 shows that the milk solids production and effective milking hectares were a

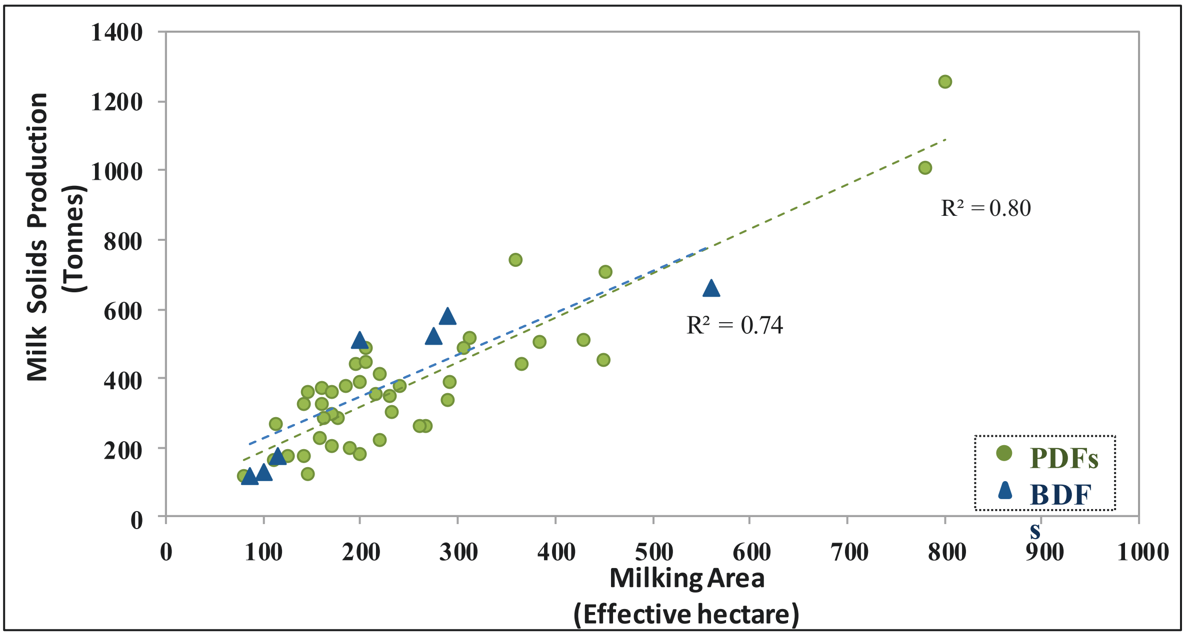

Figure 2 - 3: Relationship between Milk Solids Production and Effective Milking per Hectare

little less interdependent compared to herd size in both dairy systems; this may be due to the difference in stocking rate among farms.

In Figure 2-4, the relationship between the production intensity (milk solids production per hectare) and stocking rate (cows per hectare) is shown. For pastoral farms, it showed a moderate relation suggesting that in addition to herd size, other factors may be important in determining milk production. For barn farms, there is a strong association between production intensity and stocking rate (R^2=92) reinforcing that other factors are less important than the herd size. In other words, it suggests that as the number of cows per hectare in barns increases the milk production per hectare increases significantly.

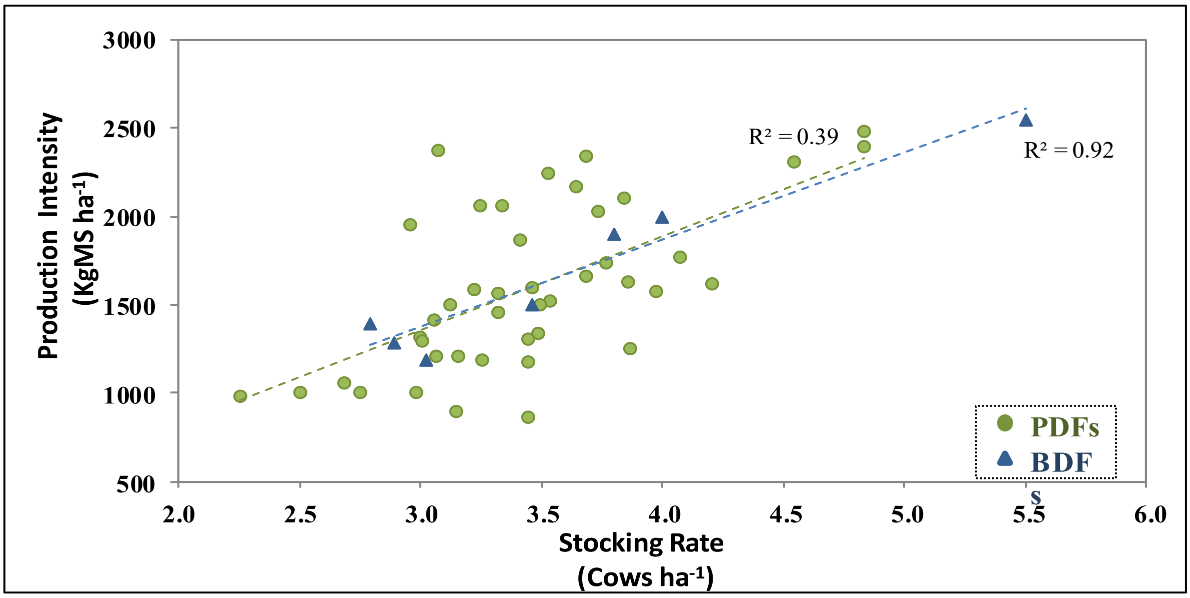

Figure 2 - 4: Relationship between Production Intensity and Stocking Rate

2.8 Distribution of Energy Sources

In Figure 2-5, the breakdown of total energy consumption into its energy input sources for PDFs reveals that electricity (35.5%) and fertilizer (29.9%) consumed most energy, followed by machinery (15.7%) and feed supplements (14.1%). Similar findings were reported by Saunders and Barber (2007) who indicated that electricity (24%) and fertilizer (36%) were the core contributors to the total energy requirements for a pastoral dairy system (PDFs) in NZ. Likewise Podstolski (2015) and Wells (2001) reported that the fertilizer and electricity are the two main drivers of energy intensification in NZ PDF systems. However in contrast to PDFs, energy input sources for BDFs indicate that most energy was consumed in electricity (34.8%), followed by imported feed supplement (24.1%) and fertilizer (16.5%).

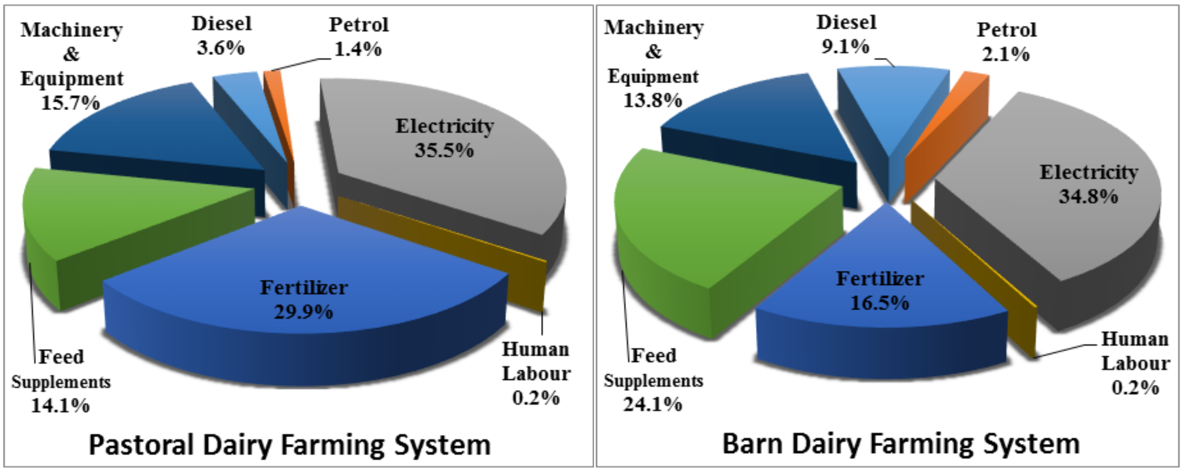

Figure 2 - 5: Percentage Distribution of Energy Sources for PDFs and BDFs Dairy Systems

2.9 Energy Consumption Patterns

2.9.1 Energy Consumption per Hectare

The total primary energy consumptions of NZ pastoral and barn dairy systems were estimated by summation of direct and indirect energy inputs. Table 2-3 demonstrates the energy consumption per hectare for both dairy systems based on different energy inputs. The result shows that on average the total primary energy consumed by pastoral dairy systems (PDFs) was 50,538 MJha^{-1} and for barn dairy systems (BDFs) was 55,833 MJ ha^{-1}. The difference in total energy footprint is 5295 MJ ha^{-1} indicating that 9.5% less energy was

Table 2 - 3: Energy Consumption of Pastoral & Barn Dairy Farming Systems (MJ ha^{-1})

	Pastoral				Barn			
Items	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Direct Energy Inputs								
Diesel	1824	778	436	4124	5099	4776	1570	15750
Petrol	687	379	113	1752	1178	458	900	2198
Electricity	17917	14626	3312	78954	19447	11206	10095	34020
Labour	86	21	46	141	114	30	55	150
Indirect Energy Inputs								
Fertilizer	15128	4139	3579	19064	9206	5071	0	16244
Feed Supplements	6937	4338	0	16124	12515	2035	10580	16655
Machinery	7959	2546	1031	15680	8274	2252	3688	10559
Total Energy Use	50538	16598	18539	108750	55833	11494	40737	69872
Output								
Milk	60571	17480	32693	94141	64121	18447	44894	96710

consumed in the PDFs compared to BDFs. In other words, barn systems are using almost 11% more energy per hectare than the pastoral system.

Among total energy inputs, electricity and fertilizer were the leading energy inputs in PDFs, while in BDFs system, electricity and imported feed supplements were the major energy inputs. However, between direct energy inputs, electricity consumption was higher in BDFs (19,447 MJ ha^{-1}) compared to PDFs (17,917 MJ ha^{-1}). The reason for this higher electricity usage in BDFs was due to more use of electrical equipment in the barn facilities. However, in both dairy systems, the high energy share of electricity indicates its heavy consumption is due to irrigation and dairy shed operations. Fuel energy in the form of diesel and petrol was also higher in BDFs compared to PDFs. As in pastoral systems (PDFs), cows are mainly fed through the grazing of pasture paddocks, which requires lower machinery usage (for pasture production and feed distribution) resulting in lower fuel consumption. In barn systems (BDFs), higher fuel consumption was due to more use of machinery involved in feed production, handling and distribution of feed to cows using barn facilities. Considering labour energy, results indicate that barn farming costs more than pastoral, as more labour may be required to operate the barn or distribute the feed to cows inside the barn.

Among the indirect energy inputs, fertilizer and imported feed supplements were the main contributors to total energy consumption. The proportion of both varied between the two dairy systems, as illustrated in Table 2-3. The energy associated with fertilizer consumption was 15,128 MJ ha^{-1} for pastoral dairy farms whereas for barn it was 9,206 MJ ha^{-1}. This difference refers to one of the barn benefits, probably due to better control of effluent collected under barn facilities, resulting in less use of synthetic fertilizers.

However, the energy use from imported feed supplements for BDFs was 12,515 MJ ha^{-1} and for PDFs it was 6937 MJ ha^{-1}. The higher energy consumption from imported feed supplements in BDFs, was due to a number of factors such as using barn facilities (especially in the winter season) which requires more feed supplements to feed the cows for the duration of using the barn, in addition to a higher stocking rate and a longer lactation period of cows. On the other hand, cows under PDFs systems mostly rely on pastoral paddocks (for pasture eating) and may only have feed supplements during feed deficit conditions or in winter at the time they are dried-off. However, there is little difference in machinery energy between the two systems; the BDFs systems possessed higher machinery energy, probably due to higher use of machinery for feed distribution to cows using the barn facilities.

The total energy consumption of each farm for both type of dairy systems plotted against the effective milking area is presented in Figure 2-6. This shows a strong relationship between energy consumption and effective milking hectares in barn farms, suggesting less variation in input management within the system. For pastoral farms a moderately strong relationship was observed, suggesting input variation within the system.

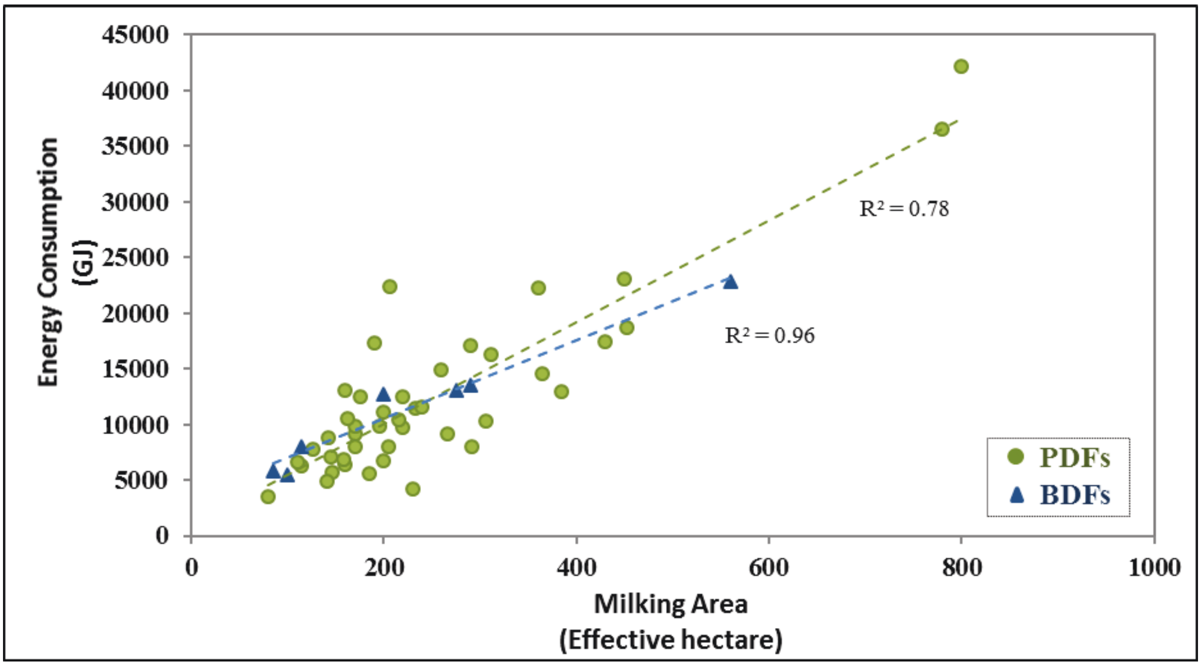

Figure 2 - 6: Relationship between Energy Consumption and Effective Milking per Hectare

2.9.2 Energy Consumption per Kilogram of Milk Solids

The results presented so far have focused on energy consumption per hectare basis. However, for a better evaluation of the different dairy farming systems, it is necessary to compare their energy consumption on a production basis as well (Bos, de Haan, Sukkel, & Schils, 2014; Gomiero, Paoletti, & Pimentel, 2008). Hence, the energy consumption of both PDFs and BDFs were compared on a kilogram milk solid (kg MS) basis to examine the energy variation among both systems. The energy consumption per kilogram of milk solids for both PDFs and BDFs systems is illustrated in Table 2-4. The result shows that on average to produce one kilogram of milk solid, 33.7 MJ of energy was required in pastoral systems, whereas for barn it was 35.8 MJ of energy. Thus, again depicting lower energy consumption in PDFs compared to BDFs, with the pastoral systems using 6% less energy input to produce one kilogram of milk solid. The energy consumption results based on kilogram of milk solids almost exhibit the same energy inputs pattern as presented by the energy consumption per hectare figures.

Table 2 - 4: Energy Consumption per kg MS in Pastoral & Barn Systems (MJ kgMS^{-1})

	Pastoral				Barn			
Items	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Direct Energy Inputs								
Diesel	1.2	0.6	0.4	2.9	3.4	3.9	1.1	12.2
Petrol	0.4	0.2	0.1	1.2	1	0.4	0.4	1.6
Electricity	12.1	10.1	1.7	57.6	12	6.6	5.3	22.6
Labour	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.1
Indirect Energy Inputs								
Fertilizer	10	4.4	2.4	21.4	6.1	3.6	0.0	11.6
Feed Supplements	4.6	3.0	0.0	12.9	8.1	1.5	5.4	9.6
Machinery	5.3	2.1	0.9	12.8	5.1	1.8	3.1	7.6
Total Energy Use	33.7	14.1	12.2	86.1	35.8	10.9	23.3	48.7

In Figure 2-7, the total energy consumption of each farm is plotted against the milk solids produced for both the dairy systems. A moderately strong correlation is observed between them, thus suggesting that energy consumption is lower on farms with smaller herd size and hence lower production and vice versa.

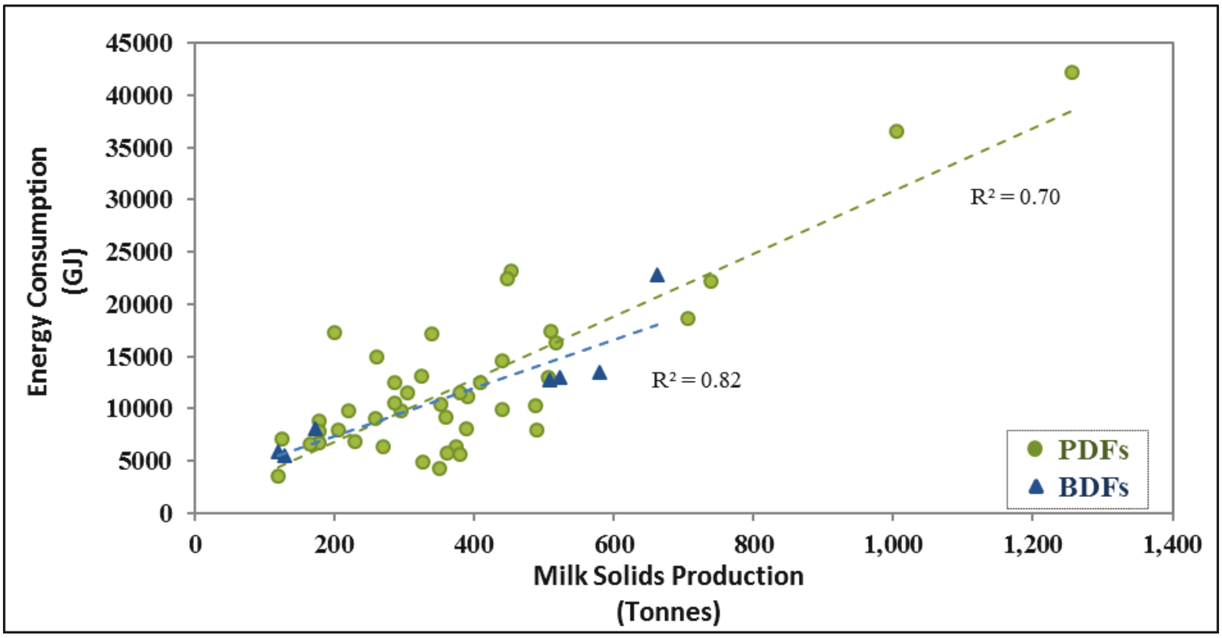

Figure 2 - 7: Relationship between Energy Consumption and Milk Solid Production

2.10 Predicting Energy Consumption for NZ Dairy Farms

The multiple linear regression model that fit can predict the energy consumption of Canterbury dairy farms with 82% and 86% variation in the training and validation data, respectively. The model given in Table 2-5 containes five variables: total electricity used at the dairy farm during the year, the nitrogen (N) applied, feed supplement brought in for the season, the total number of milking cows (MC) and type of dairy farming system; whether pastoral or barn (DS). In the model, all the coefficients included were statistically significant at less than p = 0.01 except one at less than p = 0.1 significance level. The overall model was statistically significant at less than p = 0.05.

The model showed that if the use of electricity, nitrogen fertilizer and imported feed supplements on dairy farms increase, the energy consumption will increase substantially. However, an inverse relationship between the number of milking cows and energy consumption (MJ ha^{-1}) was observed as indicated by the negative sign with the coefficient. The impact of dairy farming systems (PDFs or BDFs) contributed significantly to the energy consumption of dairy farms revealing that pastoral (PDFs) dairy farming systems were consuming less energy compared to barn (BDFs) systems.

Table 2 - 5: Multiple Linear Regression Model for Energy Consumption of Dairy Farms

Variables	Unit	Coefficient (Std. Error)
Electricity Used	MegaWatt-hours/annum (MWh)	37.2* (3.2)
Nitrogen Consumption	Tonne/Annum (t/annum)	112.7* (47.3)
Imported Feed Supplements	Tonne Dry Matter/Annum (tDM/annum)	8.0* (2.7)
Dairy Farming System	Pastoral=1 Barn=0	-7293.9** (3910.9)
Milking Cows	Number	-45.3* (4.8)
Constant	-	64133.4 * (4215.4)

* p<0.01, ** p<0.1

The final root-mean-square error (RMSE) for the training and validation models was 6848 MJ ha^{-1} and 9900.1 MJ ha^{-1}, respectively. A satisfactory regression model equation can be written as:

Energy Consumption (MJ ha^{-1}) = 64133.4+ 37.2* Electricity + 112.7* N + 8.0* Feed Supplement - 7293.9* Dairy system (Pastoral/Barn) - 45.3* Milking Cows (2-5)

The correlations between energy consumed at the dairy farm and predicted energy consumption for the training (r= 0.91) and validation (r= 0.92) data were similar. The correlation between actual and predicted Energy Consumption (MJ ha^{-1}) for training and validation are given in Figure 2-8 and Figure 2-9, respectively.

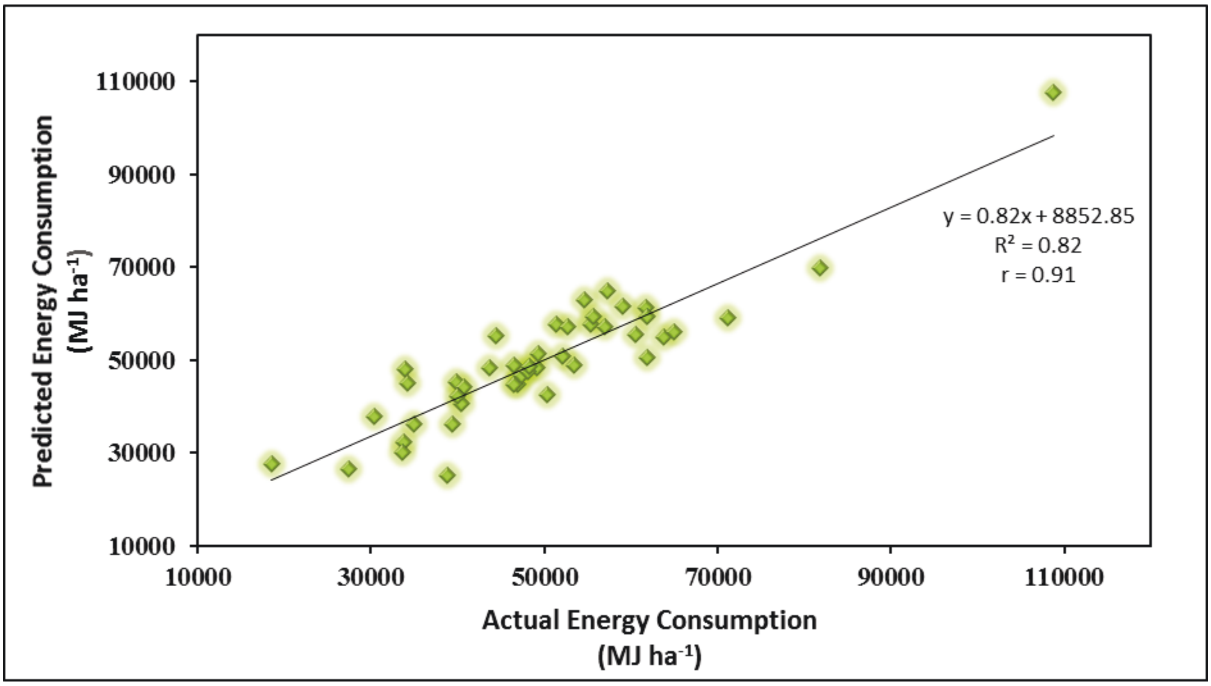

Figure 2 - 8: Correlation between Actual and Predicted Energy Consumption through MLR for Training Data

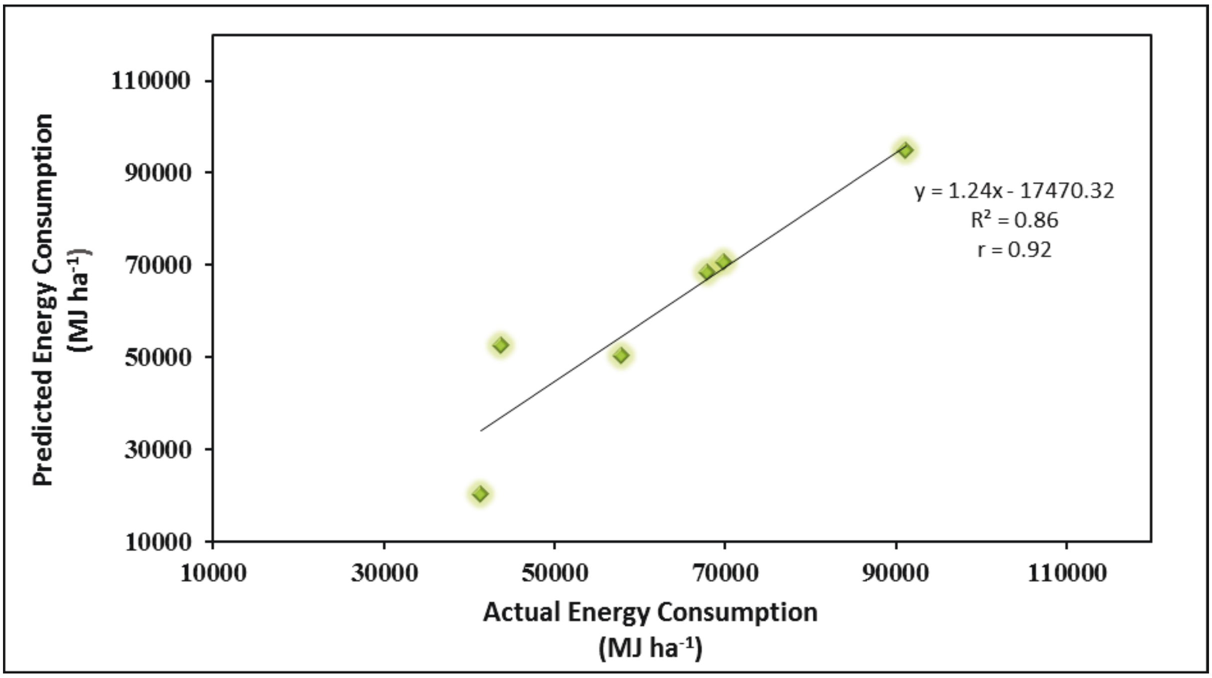

Figure 2 - 9: Correlation between Actual and Predicted Energy Consumption through MLR for Validation Data

2.11 Discussion

The initial studies of energy estimation carried out on Canterbury dairy farms have showed an energy consumption about 9,100 MJha^{-1} (McChesney, 1979). Wells (2001) research on energy intensity of dairy farms served as a baseline and shaped the energy analysis for sustainable agriculture in New Zealand, where he reported total energy use for Canterbury dairy farms to be 36,500 MJha^{-1}. Whereas, Barber (2008) determined energy intensity of a single Lincoln University dairy farm as 43,400 MJha^{-1}, while Latham (2010) identified energy use of a single Canterbury modelled farm as 33,200 MJha^{-1}. In this current research study, the energy consumption of pastoral (PDFs) dairy systems is higher compared to previous research studies (Barber, 2008; Latham, 2010; McChesney, 1979; Wells, 2001). This increasing trend in the energy consumption of Canterbury dairy systems may be attributed to the increased stocking rates, number of dairy cows and effective milking hectares, resulting in increased intensification within pastoral dairy systems. It should be noted, however, in the study by Podstolski (2015), he reported energy intensity as 51,300 MJha^{-1} for Canterbury pastoral dairy systems. Compared to that, the energy consumption of PDFs is slightly lower in this current study. This may be due to methodological and data sampling size differences[7].

Although energy intensification has been observed compared to previous studies, however, in this current research study, the pastoral systems (PDFs) do consume less energy per hectare and per milk production basis, when compared to barn dairy farming systems (BDFs).

From a systems comparative perspective, when considering the energy consumption for both PDFs and BDFs systems, the main source of direct energy was electricity in both systems due to its significant importance in irrigation and milking shed operations. Among the indirect energy sources, fertilizer and feed supplements showed the greatest variation between the two dairy systems, with PDFs having greater energy usage in relation to fertilizers, and BDFs greater usage of imported feed supplements. BDFs also have higher milk solid production per cow and per hectare, in part due to the longer lactation period of the cows, although this does not compensate for the greater use of energy inputs.

2.12 Conclusion

Energy consumption estimation in agriculture has emerged as an important tool for sustainable farming. The main purpose of this study was to measure energy consumption of NZ pastoral (PDFs) and barn (BDFs) dairy farming systems based on their direct and indirect energy inputs.

The results indicate that total energy consumption of pastoral (PDFs) and barn (BDFs) dairy systems were found to be 50538 MJ ha^{-1} and 55833 MJ ha^{-1} respectively. Among total energy consumption, electricity (35.5%) and fertilizer (29.9%) were the main energy inputs in PDFs, while in BDFs, electricity (34.8%) and imported feed supplement (24.1%) were the leading energy inputs. From a system comparative perspective, the energy consumption was better in PDFs compared to BDFs both per hectare and milk production basis, as PDFs consumed 9.5% and 6% lower energy inputs respectively, compared to BDFs. Nevertheless, from an energy consumption perspective, results are in the favour of the New Zealand low-

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[7] Podstolski (2015) used Dairybase data for the season 2012-13 to measure energy inputs for NZ dairy farms and for specific Canterbury region, his data sample comprised only 20 pastoral dairy farms.

input pastoral based grazing systems, showing that energy can be conserved by 9.5% in PDFs over the BDFs system, through less energy usage. Furthermore, the multiple linear model was developed for prediction of energy consumption based on energy inputs (electricity, nitrogen fertilizer and imported feed supplement), the number of milking cows and farm management system (PDFs/BDFs).

Chapter 3

The Carbon Footprint of Energy Consumption in Pastoral and Barn Dairy Farming Systems: A Case Study from Canterbury, New Zealand[8]

Abstract

Dairy farming is continuously evolving to more intensive systems of management, which require high utilization of energy inputs. The utilization of these energy inputs in farming contributes to climate change both with on-farm emissions from the combustion of fuels, and by off-farm emissions due to production of farm inputs (fertilizer, feed supplements). Hence, this study aims to evaluate energy related carbon footprints of pastoral (PDFs) and barn (BDFs) dairy systems located in Canterbury, New Zealand. Research data were collected through survey questionnaire and literature review methods. In this study, the carbon footprints were measured as a sum of direct and indirect carbon emissions (CO_2) released from energy consumption (energy inputs).

The results showed that on average, the carbon footprints of pastoral (PDFs) and barn (BDFs) dairy systems were 2857 $kgCO_2\ ha^{-1}$ and 3379 $kgCO_2\ ha^{-1}$ respectively, whereas for production of one tonne of milk solids each system released carbon dioxide (CO_2) emissions at 1920 $kgCO_2\ tMS^{-1}$ and 2129 $kgCO_2\ tMS^{-1}$ respectively. The carbon emission difference between the two systems, indicates that the BDFs system have 18% and 11% higher carbon footprints than the PDFs system, both per hectare of farm area and per tonne of milk solids respectively. The greater carbon footprints of BDFs were due to greater use of imported feed supplements, fossil fuels (diesel and petrol) and machinery energies. In both dairy systems the carbon footprints due to indirect energy inputs are higher than the carbon footprints of direct energy inputs. A multiple linear regression model was developed for prediction of carbon footprints (CO_2) of NZ dairy farms based on their energy consumption and it was found that electricity, nitrogen and sulphur fertilizers and imported feed supplements were the significant factors in predicting carbon emissions of Canterbury dairy

[8] This chapter has published in the Journal of "Sustainability". The main work was carried out by Hafiz such as concepts development, data collection, analysis and writing the manuscript. All co-authors provided feedback on development of the manuscript.

farms. Further, reduction in carbon footprints of NZ dairy systems through better energy management or by improving energy efficiency was recommended.

Keywords*:* Carbon Footprints, Pastoral Dairy Farming System (PDFs), Barn Dairy Farming System (BDFs),

3.1 Introduction

Energy consumption, water use and environmental footprints are becoming the major challenges in an agro-food sector that is considered a significant contributor to climate change problems (Smith et al., 2007). Agricultural and livestock activities are responsible for primary greenhouse gases (GHGs) emissions, such as CH_4, N_2O amd CO_2, and contributed around 10-12% to global anthropogenic GHG emissions (Crosson et al., 2011; Smith et al., 2007). The Food and Agriculture Organization (2006) stated that the entire livestock sector accounted for 18% of global GHG emissions, when considering the whole production chain- from land use and feed production to waste management. However, recent studies attribute lower quotas from 2 to 4 percent of total GHG emissions to the livestock sector, while crediting 20% of that livestock emission to milk production (Food and Agriculture Organization, 2016; Gerber et al., 2013).

Dairy farming is a major contributor to the New Zealand economy (export value $NZ13.4 billion), but also to NZ total greenhouse gas (GHG) emissions (DairyNZ & LIC, 2017b). The agriculture sector accounts for 49% of NZ gross emissions with a 36% share coming from pasture-based farming systems (Beukes, Gregorini, & Romera, 2011; Beukes, Gregorini, Romera, Levy, & Waghorn, 2010). Among dairy farming systems, the primary greenhouse gases (GHG) are methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emitted from livestock ruminant, agricultural soils and energy consumption respectively. During 1990-2014, NZ agricultural emissions increased by 15% due to intensification and growth in dairy productions and the associated emissions (MfE, 2016). Thus, identification of dairy farming systems with minimum environmental emissions is necessary.

New Zealand dairy farming is continually developing more intensive systems of management, which involve higher utilization of durable and non-durable inputs (Parliamentary Commissioner for the Environment, 2004). These inputs are responsible for significant direct and indirect fossil energy consumption, which produces notable emissions of carbon dioxide (CO_2). On farm, direct emission of carbon dioxide occurred due to consumption of fossil fuels in machinery involved in different dairy farming operations. While off-farm, indirect emissions occurred in other industrial sectors, which supply the farm inputs (fertilizers, feed supplements, machinery etc.) consumed in the farming operations or processes (Intergovernmental Panel on Climate Change, 2006). In other words, the consumption of fossil energy in farming activities contributes to climate change both with on-farm emissions from the combustion of fuels, and by off-farm emissions due to production and transportation of agricultural inputs to the farm (West & Marland, 2002). Consequently, the more efficient use of fossil energy resources together with an increased use of renewable energies can play a key role in the development of sustainable dairy production systems.

New Zealand is renowned for its traditional pasture-based dairy farming system (PDFs), where farmers aim to increase their profits by minimizing production costs through maximizing the proportion of grazed grass in the diet of lactating cows (Basset-Mens et al., 2009; O'Brien et al., 2014). Over recent decades, NZ pasture-based dairy systems (PDFs) have intensified due to higher financial benefits in the dairy sector, resulting in increased use of farm inputs (fertilizer, water, electricity, fuel etc.) in dairy systems to produce more milk per hectare of grassland (Basset-Mens et al., 2009; PCE, 2004). This intensification has put NZ pastoral dairy systems under huge pressures from both the general public and regulatory bodies due to their perceived environmental impacts such as N leaching and phosphorous run-off to waterways (PCE, 2004). Additionally, the growing dairy sector has significantly contributed to NZ greenhouse gas emissions, which impacts on NZ's ability to reduce its emissions below 1990s level under the Paris Accord[9] Agreement (Basset-Mens et al., 2009; Beukes et al., 2011; Ministry for the Environment, 2019). In contrast to NZ's pastoral system, barn dairy systems have been a relatively recent introduction in NZ as a solution to animal welfare, soil structure damage and wider environmental challenges (Pow et al., 2014). But the use of barn facilities requires further intensification of the system, in

[9] Under the Paris Agreement, the New Zealand has a target to reduce its greenhouse gas emissions (GHG) by 30% below 2005 levels by 2030. This target is equivalent to 11% below 1990 levels by 2030 (Ministry for the Environment, 2019).

terms of stocking rate and energy inputs to make the system profitable, making it difficult to achieve both financial and environmental benefits simultaneously (Newman & Journeaux, 2015).

Currently, reducing greenhouse gas emissions from NZ dairy systems is a critical challenge for the NZ dairy industry. As with the Paris Accord agreement, New Zealand has commitments to reduce its greenhouse gas emissions up to 30% below 2005 levels by 2030 (Ministry for the Environment, 2019). Consequently, recently New Zealand's government proposed a "Zero Carbon Bill" which sets new emission reduction targets for whole NZ industries including the dairy sector, such as carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions which have to reduce to net zero by 2050 (DairyNZ, 2019). Moreover, there are number of research studies in New Zealand which evaluate the environmental impacts of NZ dairy systems, based on the major CH_4 and N_2O emissions (Beukes et al., 2011; Beukes et al., 2010), but there is no study which compares energy related carbon footprints between NZ contrasting dairy systems (such as PDFs and BDFs). Under these situations, the NZ dairy sector needs to take a serious look at the ways of energy expenditure and improve energy efficiency of dairy farming systems in order to achieve future emission reduction targets through reducing energy related carbon emissions. Thus, a comparative study based on carbon footprints of NZ contrasting dairy systems is compulsory.

In NZ literature, several studies have estimated the carbon footprints (CO_2) of agricultural systems based on energy consumption. In the dairy sector, Wells (2001) evaluated for the first time the energy related carbon footprints of NZ pastoral systems from eight different regions and found that Canterbury dairy systems are more energy intensive and have higher carbon footprints compared to other dairy systems in other regions, mainly due to the higher use of irrigation. Later, Saunders and Barber (2007) compared NZ and UK dairy industries based on energy use and greenhouse gas emissions in response to a "*Food Miles*" debate[10]. They considered "cradle to gate" farm energy inputs used for milk production along with transportation energy to compare greenhouse gas emissions of both systems and

[10]Food Miles was an issue which arose in UK, Germany and other countries due to environmental concerns over food transportation. The main argument was that the longer transport distance (food miles) involved more energy consumption, which released higher greenhouse gas emissions and caused global warming (Saunders et al., 2006).

acknowledged the NZ dairy system as more emission efficient than the UK system. Afterward, Barber (2008) estimated carbon footprints of a single Lincoln University dairy farm (LUDF) and found higher carbon footprints in LUDF compared to a typical NZ dairy farm. In another study, Latham (2010) tried to compare the carbon footprints of a Canterbury dairy farm with two intensified farms from the McKenzie district, but due to inaccessibility of data, his analysis was restricted to a Canterbury dairy farm only. Moreover, Latham (2010) findings were inconsistent with previous NZ research, in part due to its different methodological approach and using only one farm (data) as the Canterbury model farm, which would not be truly representative data for all farms within the Canterbury region.

However, in international literature, there are number of research studies that have evaluated organic and conventional pastoral dairy systems based on energy use and associated greenhouse gas emission. They found lower greenhouse gas emissions in organic systems compared to conventional systems (Bos et al., 2014; Cederberg & Mattsson, 2000; Thomassen, van Calker, Smits, Iepema, & de Boer, 2008). Some other studies have evaluated carbon footprints (CO_2) of dairy systems through considering only direct energy inputs (fossil fuel, electricity) and found fossil fuel especially diesel as the leading source of CO_2 emission in total carbon footprint compared to electricity consumption (Murgia, Todde, Caria, & Pazzona, 2013; Todde et al., 2018a). From a system comparative perspective, Flysjö, Henriksson, Cederberg, Ledgard, and Englund (2011) compared NZ's pastoral dairy system with a barn system from Sweden and found lower carbon footprints in the NZ pastoral system over the Sweden barn system. Similarly in another study, O'Brien et al. (2012) compared energy related environmental impacts of pastoral and barn dairy systems based on a life cycle assessment (LCA) approach and found greater environmental impacts in the barn system than the pastoral one, based both on milk production and farm area. But similarly to Latham (2010), this study could be considered limited due to considering only two research farms' data. Under these circumstances, it is difficult to directly compare dairy systems between different countries due to huge variation between systems' boundaries, methodological approach and representative data issues for dairy systems. Moreover, in NZ the literature is very thin regarding carbon footprints evaluation between contrasting dairy systems. From a systems perspective, there is however no study in New Zealand which has evaluated energy related carbon footprints of pastoral (PDFs) and barn (BDFs) dairy systems. In this context, there is need of research study which assesses energy related carbon footprints of NZ pastoral (PDFs) and barn (BDFs) dairy systems to identify sustainable dairy systems for the future of the NZ dairy industry.

Therefore, the purpose of this research study was to estimate carbon footprints (CO_2) of NZ pastoral and barn dairy systems based on their energy consumption. Further, this study developed a carbon footprint prediction model to predict energy related carbon emissions (CO_2) for Canterbury dairy farms.

3.2 Material and Methods

This study was carried out on pastoral (PDFs) and barn (BDFs) dairy systems from Canterbury, New Zealand. Canterbury is one of the important dairy regions of NZ, which comprises 10% dairy herds and 16% of NZ dairying land (DairyNZ, 2017b). This study only measured carbon footprints in the form of CO_2 emissions associated with energy consumption, without considering CO_2 emissions from agricultural soils.

The data were collected from two different sources: literature review and survey questionnaire. For this purpose, 50 dairy farms data (BDFs =7 & PDFs = 43) for the season 2016-17 were collected from Canterbury, New Zealand, through face-to-face interview method. The carbon footprints of PDFs and BDFs systems were analysed based on CO_2 emission from direct and indirect energy sources including fuel, electricity, fertilizers, imported feed supplements and machinery. In this study, the system boundary was set at farm level "from cradle-to-farm gate" excluding the post-processing components of milk when it leaves the farm gate i.e. transport and waste disposal components of the product's life cycle were not considered beyond the farm gate (as shown in Figure 3-1). Thus, carbon footprints (CF) of PDFs and BDFs systems were estimated as the sum of the input factors (Ai) multiplied with their appropriate CO_2 emission coefficients (Ci), (equation 3-1):

$$CF = \sum AiCi \tag{3-1}$$

For converting each farm input into carbon emissions (CO_2), different conversion factors or coefficients were selected after investigation and evaluation of different studies. In this study, farm inputs were first converted into energy equivalents and then into carbon emissions (CO_2).

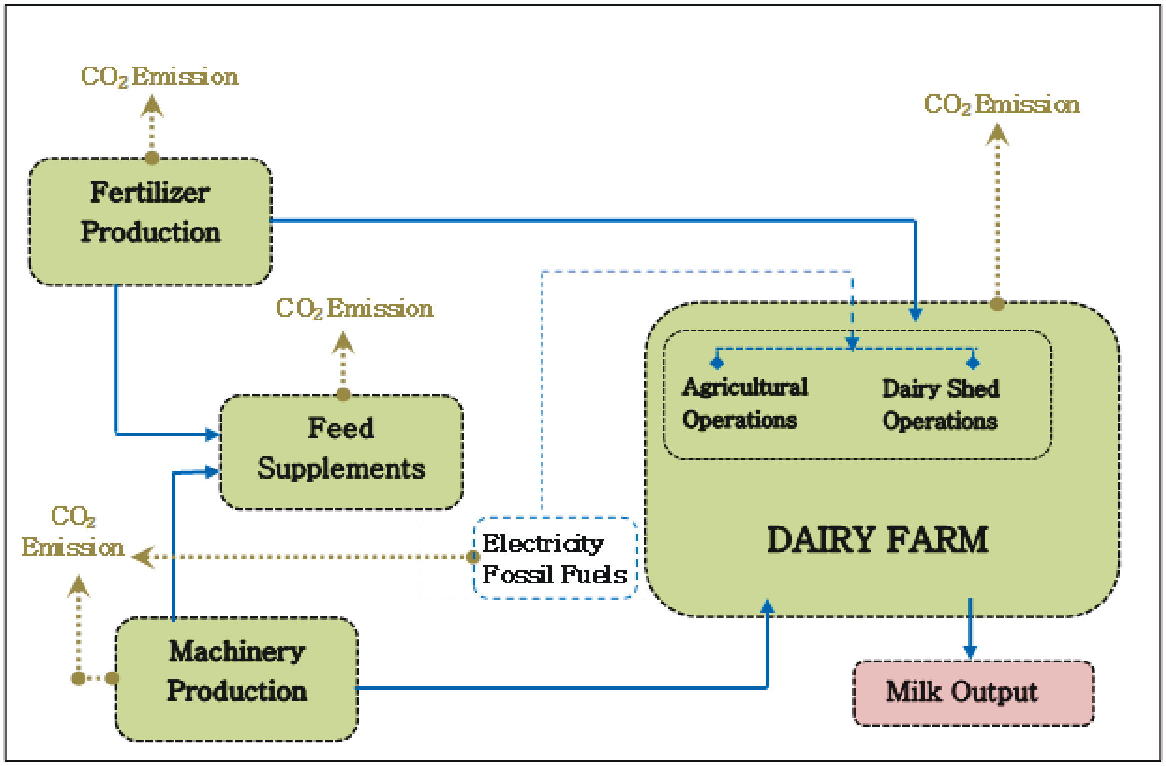

Figure 3 - 1: Dairy Systems' Boundaries, Respective Inputs and Associated CO_2 Emissions

3.2.1 Fossil Fuel

Diesel and petrol are the leading fuel inputs used in NZ dairy farming systems. The combustion of fossil fuels occurs during different farming operations such as tillage, harvesting, fertilizer application, irrigation and spraying etc. emitting carbon dioxide (CO_2) gas into the atmosphere (Lal, 2004; Safa & Samarasinghe, 2012). Diesel is mainly used in tractors, trucks and heavy machinery, while petrol is only used in motorbikes and light trucks etc. Comparatively, the usage of diesel was higher for farm machinery; because most of the farm machinery is based on diesel engines due to their benefits such as being durable, strong and having higher efficiency than the petrol engine (Kitani, 1999). For measuring the fuel consumption in tractors, there are several ways available based on power of the tractors; but the influence of numerous factors such as soil conditions, air pressure, height above sea level, humidity and temperature, fuel consumption etc. restricted those methods to specific areas (Bertocco, Basso, Sartori, & Martin, 2008; Safa & Samarasinghe, 2012; Serrano, Peça, da Silva, Pinheiro, & Carvalho, 2007). Also, these methods are only effective in the prediction of fuel consumption for diesel engines under a full-load, but under fractional loads and variable speed conditions, again these methods are not applicable (Siemens, Bowers, & Holmes, 1999).

In this study, total fuel consumption for each dairy system were determined through the survey questionnaire. For the energy coefficients and emission factors for diesel and petrol, different studies and reports were investigated. Hence, the most recent and dairy farming related energy coefficients for diesel and petrol were taken as 45 and 42 MJ/litre (MED, 2012; Podstolski, 2015), and the base CO_2 emissions factors associated with diesel and petrol were considered as 0.07 and 0.06 respectively (Nebel, 2008).

3.2.2 Electricity

In Canterbury dairy farming systems, electricity is mostly consumed in irrigation and dairy shed operations. For irrigation, electricity is mainly used for pumping water from rivers and wells, and its consumption fluctuates according to type of irrigation system, water table depth and crop water requirements (Safa & Samarasinghe, 2012; Stout, 1990; Vlek, Rodríguez-Kuhl, & Sommer, 2004). For dairy sheds, electricity is mainly used to operate milking parlours for the milk extraction process along with water heating, ventilation and lighting purposes. According to Carran, Ledgard, Wedderburn, and Jollands (2004), in the average NZ pastoral system, 59% of direct energy inputs are associated with electricity consumption, and the major portion of this total electricity is consumed in the dairy shed with the rest used for irrigation pumping and dairy effluent treatment. Based upon a pastoral system, Hartman and Sims (2006) distributed electricity consumption into different dairy shed operations on a per cows basis encompassing water heating (51 kWh cow^{-1}), milk cooling (34 kWh cow^{-1}), milk machinery (29 kWh cow^{-1}), water pumping (29 kWh cow^{-1}) and lighting (20 kWh cow^{-1}) etc. Therefore, the major carbon emission due to electricity was from dairy sheds. On-farm, there are no direct emissions from electricity consumption, but off-farm electricity generation releases a significant amount of carbon (CO_2) emissions into the atmosphere due to the burning of fossil fuels. In New Zealand, around two-thirds of electricity is generated through renewable energy sources (Safa & Samarasinghe, 2012), so the use of more renewable energy sources can reduce carbon emission from electricity generation.

In a perfect situation, the conversion factor for electricity is 3.6 MJ/kWh. This conversion factor does not consider any electricity generation and conversion inefficiencies. Given the potential for inefficiencies in the system, the primary energy content of electricity was considered as 8 MJ/kWh MED (2012). Moreover, the amount of carbon (CO_2) emissions released from electricity generation depends on the proportion of renewable and fossil energy consumption, thus based on grid-mix, the average electricity emission factor was taken as 0.03 kg CO_2/MJ (Nebel, 2008). Thus, in this study, annual electricity consumption for each system was determined through questionnaire answers. Then multiplying the electricity amount with the carbon emission factor, total carbon dioxide (CO_2) emission for electricity was calculated.

3.2.3 Fertilizer

The increase in farm area and herd size have not only contributed to more production but have also led to the intensification of pastoral land use. Over the last two decades, the intensification of the New Zealand dairy industry has noticeably increased the farm energy consumption; especially fertilizers and electricity as leading energy inputs into Canterbury dairy farming systems (Ilyas et al., 2019; Podstolski, 2015). The use of synthetic fertilizers in NZ dairy systems has not only increased the energy usage, but also the environmental impacts such as greenhouse gas emissions and contamination of waterways (Fertilizer Association, 2019; Snyder, Bruulsema, Jensen, & Fixen, 2009).

Among energy consumption, fertilizer is one of the major energy inputs contributing significantly to greenhouse gas emissions of dairy farming systems after animal related emissions (such as methane from enteric fermentation and nitrous oxide from excreta). The Ledgard, Boyes, and Brentrup (2011) study suggests that fertilizers and lime contributed about 15% to on-farm GHG emissions or more than 50% of off-farm emissions (CO_2), in part because off-farm the production and manufacturing of synthetic fertilizers based on fossil fuels resources, emit massive carbon emissions (CO_2) into the atmosphere (Kitani, 1999). Among the fertilizers, nitrogen fertilizer is mostly applied to dairy land and its use has been increased seven-fold between 1991 to 2009, with their average use of 120kg N/ha in 2009 on New Zealand dairy systems (Ministry for Primary Industries, 2012).

In Canterbury dairy systems, farmers use ammonia-urea and superphosphate more than other fertilizers. In this study, fertilizer amount was recorded by fertilizer type used in the two systems. Subsequently the emissions associated with each fertilizer type were estimated by breaking down each fertilizer into their essential components (N, P, K, S), and then multiplied with their relevant carbon emission factors. Thus, the embodied energy involved in manufacturing each fertilizer component N, P, K, S were taken as 64.1, 28.4, 17.8 and 3.24 MJ kg^{-1} respectively (Wells, 2001), while corresponding emission factors were considered as 0.04, 0.08, 0.06, 0.71 $kgCO_2$/MJ respectively (Wheeler, 2018).

3.2.4 Imported Feed Supplements

The New Zealand traditional pasture-based dairy system is particularly built on low production costs with a high proportion of grazed grass in the diet of lactating cows (Basset-Mens et al., 2009; O'Brien et al., 2014). In fact, there is wide evidence that increasing the proportion of pasture in a cow's diet reduces production costs at an increasing rate (Dillon, Hennessy, Shalloo, Thorne, & Horan, 2008; Doole, 2014). However, the NZ dairy industry has intensified over the last few decades (Doole, 2014), which has moved the NZ traditional dairy system away from the purely pasture-based. Consequently, the use of imported feed supplements has increased in pasture-based dairy systems (PDFs) to meet feed deficit conditions and reduce the production variability across the season (Doole, 2014; Jensen, Clark, & Macdonald, 2005). Consequently, the NZ dairy industry has categorized dairy farming into five production systems based on the percentage of imported feed supplements usage (IFS) from System 1 with 0% IFS to System 5 with more than 31% IFS (DairyNZ, 2017a). However, the usage of imported feed supplements is higher in the barn dairy system (BDFs), probably due to the higher stocking rate and more intensive nature of the system. The most common types of imported feed supplements used in NZ dairy systems are grass silage, maize silage, hay, straw, palm kernel, concentrate etc. As production of imported feed supplements involves fossil energy consumption and released carbon dioxide emissions into the atmosphere, it is considered as an indirect source of carbon emissions (CO_2) in this study.

In this study, the amount of imported feed supplements were estimated for each dairy system through the survey questionnaire. Whereas, the values for energy coefficients and carbon emissions factors for each feed supplement were considered after careful investigation and evaluation of different studies, as shown in Table 3-1.

Table 3 - 1: Emission Factors for Feed Supplements used in PDFs and BDFs Systems

	Grass Silage	Maize Silage	Hay	Grains	Concentrates	Straw	References
Energy Coefficients (MJ/Kg DM)	1.781	1.564	1.329	3.905	1.800	0.187	Wheeler (2018)
Emission Factors ($KgCO_2$/MJ)	0.08	0.1	0.09	0.12	0.08	0.13	

3.2.5 Machinery and Equipment

Dairy farming is constantly developing more intensive mechanization systems of management, in which utilization of agricultural machinery is increased to accomplish large farming operations with minimum human power. This can result in increased depletion of natural resources as well as the emission of greenhouse gases into the atmosphere (Murgia et al., 2013). During the last century, the usage of agricultural machinery especially tractors increased in agriculture, with the number of tractors worldwide climbing from 11 to 28 million between 1961 and 2006 (Safa & Samarasinghe, 2012).

In agriculture, most commercial energy is consumed for manufacturing and operation of agricultural machinery (Safa & Samarasinghe, 2012; Stout, 1990). According to Kitani (1999), four different steps are involved in the estimation of energy requirements for producing and repairing agricultural machinery: first, the energy needed for producing the raw materials; second, the energy involved in the manufacturing process; third, the energy used for transporting the machines to the consumer; and last, the energy consumed in repairs and maintenance. In New Zealand dairy systems, tractors and self-propelled machines (utes, motorbikes) are used for different farming activities. To compute the annual energy input from tractors and other farming equipment, it is essential to know the mass (kg), energy equivalent, working life duration and average surface where the machine is used annually (Safa et al., 2011). In this study, the estimated life of machinery was taken from the ASAE Standard D497.7 (ASAE, 2011), the annual use of different machinery was assessed through the survey questionnaire, and the average weight of the different machinery was taken from Wells (2001). Based on the energy consumption involved in the production and repair of farm machinery, Wells (2001) has estimated energy coefficients and emission factor values for different machinery used in NZ dairy systems. Hence, in this study, the energy coefficients and CO_2 emission values for machinery are considered as 160 MJ/kg and 0.08 $kgCO_2$/MJ respectively (Wells, 2001).

In dairy sheds, rotary and herringbone were the most common types of milking parlours used in both type of dairy systems. Similarly to Wells (2001), to determine the carbon emissions related to milking parlour energy, in this study the emission factor used was 0.1 $kgCO_2$/MJ of shed energy[11].

3.2.6 Carbon Footprint Prediction Model

Multiple linear regression models have been widely used in dairy farming studies for developing linear models for different variables. Multiple linear models define the linear relationship between multiple explanatory variables for prediction of a dependent variable (Gujarati, 2009; Shine et al., 2018; Todde et al., 2017). Thus, in this study, the relationships between carbon footprints (CO_2) and energy inputs and production indicators were analysed to determine the factors contributing significantly to the carbon footprints of dairy systems. As carbon footprints (CO_2) are derived by multiplication of individual energy components with emission factors; the differences between these factors and their energy sources are likely to not be very different (Wells, 2001). So, strong correlation between carbon footprints (CO_2) and energy based direct and indirect inputs were expected and found. Nevertheless, a univariate variable selection method was employed to select highly correlated variables to carbon emission for linear prediction. Variables significant at $p = 0.05$ were retained in the model (Shine et al., 2018). Furthermore, a binary variable for the dairy system was also included in the model to determine the influence of different farm management systems (PDFs & BDFs). Hence, a multiple linear regression model to predict carbon footprints of dairy farming systems was developed as equation (3-2):

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i} + \beta_6 X_{6i} + \varepsilon \quad (3\text{-}2)$$

[11] Shed energy based on number of cups calculated by the following equation (see chapter 2, section 2.5.3) $Shed\ energy\ (MJ) = (24.2 * x + 293) * 1000$ (Where x = number of cups of the milking parlour)

Whereas

Y_i = Carbon emission (CO_2 ha^{-1}) in i^{th} dairy farm

i = *1,2,3…….,50 dairy farms*

β_0 =Intercept,

β= independent variables fixed effects,

X_{1i}= total electricity used in i^{th} dairy farm,

X_{2i}= total nitrogen applied in i^{th} dairy farm,

X_{3i}= total sulphur applied in i^{th} dairy farm,

X_{4i}= total feed supplements consumed in i^{th} farm over the year,

X_{5i}= dairy farming system of the i^{th} dairy farm *(Pastoral=1 or Barn=0)*

X_{6i}= number of effective milking hectares in i^{th} dairy farm and 'ε' the error term.

Correlation between independent variables (multi-collinearity) exists, which may lead to model estimation bias. To detect and avoid that model bias, a Variance Inflation Factor (VIF) is used. Variables with threshold level less than 10 are not affected by multi-collinearity and were included in the model. The model development was done on the randomly selected training data and its predictions were verified while applying on validation data. The Model goodness to fit was also assessed by root mean square error (RMSE) (Gujarati, 2009).

3.3 Results

3.3.1 Carbon Footprints of PDFs and BDFs Dairy Systems

Table 3-2 shows carbon footprints of NZ pastoral (PDFs) and barn (BDFs) dairy farming systems (per hectare basis). In this study, carbon footprints were measured as a sum of direct and indirect carbon emission (CO_2) released from energy consumption (energy inputs). On average, total carbon footprints of pastoral and barn dairy systems were 2857 kgCO_2 ha^{-1} and 3379 kgCO_2 ha^{-1} respectively. When evaluating the contribution of individual energy inputs to total carbon footprints, fertilizer (25%) and machinery and equipment (27%) were the dominant sources of carbon emissions (CO_2) in pastoral (PDFs) systems. This is due to the high consumption of fertilizers (especially N) to grow more pasture in order to meet feed demand and the use of milking equipment for milk extraction. In barn dairy systems (BDFs), imported feed supplements (30%) and machinery and equipment (24%)

were the leading energy inputs contributed to total carbon footprints, because of the high usage of imported feed supplements and milking shed energy. The difference in total carbon footprints between the two dairy systems is 522 $kgCO_2$ ha^{-1}, a 15% lower carbon emissions (CO_2) in the PDF system compared to the BDF system. In other words, the pastoral system is 15% more emission efficient than the barn dairy system, suggesting that the pastoral system is potentially more sustainable or climate friendly than the barn system.

In comparison to previous NZ studies, Wells (2001) estimated the carbon footprints of NZ pastoral (PDFs) dairy systems across different regions of New Zealand. On a hectare basis, Wells (2001) found the carbon footprint as 2100 $kgCO_2$ ha^{-1} for Canterbury PDFs system. Similarly, Barber (2008) found energy related carbon footprints for a Lincoln University dairy farm (single farm) as 2315 $kgCO_2$ ha^{-1}. Compared to these studies, carbon footprints observed in this current study for PDFs systems are 26% and 19% lower respectively, suggesting that the carbon footprints of pastoral systems have increased over the time, in part due to dairy intensification and probably higher consumption of electrical, fertilizer and feed supplement energy inputs.

Table 3 - 2: Carbon Footprint of Pastoral and Barn Dairy Farming Systems ($kgCO_2$ ha^{-1})

	Pastoral				Barn			
Inputs	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Direct Inputs Emission								
Diesel	121	52	29	274	339	317	104	1046
Petrol	45	25	7	116	78	30	59	145
Electricity	597	487	110	2629	647	373	336	1133
Indirect Inputs Emission								
Fertilizer	708	243	151	1306	499	390	0	1276
Feed Supplements	602	428	0	1785	1015	204	656	1306
Machinery	784	253	96	1561	801	219	357	1042
Total Emission	2857	781	1190	5052	3379	705	2236	4348

Based on direct energy inputs, the carbon footprints for PDFs and BDFs systems were found as 763 $kgCO_2$ ha^{-1} and 1064 $kgCO_2$ ha^{-1} respectively. Among direct energy inputs, electricity emission ranks first in both dairy systems with 597 $kgCO_2$ ha^{-1} and 647 $kgCO_2$ ha^{-1} respectively. The reason behind this higher electricity emission in both systems was due to more electricity consumption for irrigation and milk extraction operations, also observed by Carran et al. (2004) and Wells (2001). From a system comparative perspective, electricity emission is slightly higher in the barn system (BDFs), which is probably due to more use of electricity in the barn facilities because of lighting, cleaning and effluent management activities. However, the main carbon emission difference between direct energy inputs of both dairy systems was due to diesel consumption, which is higher in barn dairy systems, probably due to more fuel requirements for feed management activities such as crop production, harvesting and feeding the cows inside the barn facilities. Compared to petrol, the diesel emission was higher in both dairy systems, due to more consumption of diesel for farm machinery such as tractors involved in on-farm operations (soil preparation, crop production, harvesting etc), while petrol was only used in motorbikes and light vehicles used as transport both on-farm and for travelling to market.

The on-farm consumption of indirect energy inputs released carbon (CO_2) emissions were 2094 $kgCO_2\ ha^{-1}$ and 2315 $kgCO_2\ ha^{-1}$ respectively for PDFs and BDFs systems. Among indirect energy inputs, fertilizer (708 $kgCO_2\ ha^{-1}$) and machinery and equipment (784 $kgCO_2\ ha^{-1}$) were the leading emission sources in PDFs systems, while in BDFs systems, imported feed supplements (1015 $kgCO_2\ ha^{-1}$) and machinery and equipment (801 $kgCO_2\ ha^{-1}$) were the main indirect emission sources. Apart from machinery and equipment, higher feed demand was the key factor which makes fertilizer and imported feed supplements prominent sources of indirect emissions in both pastoral (PDFs) and barn (BDFs) dairy systems respectively. Overall, the carbon footprints due to indirect energy inputs are higher than the carbon footprints of direct inputs in both systems.

Table 3 - 3: Carbon Footprint for PDFs & BDFs Dairy Systems ($KgCO_2\ tMS^{-1}$)

	Pastoral				Barn			
Inputs	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Direct Inputs Emission								
Diesel	81	41	24	193	229	261	75	813
Petrol	29	16	6	79	49	25	28	104
Electricity	403	338	58	1918	392	219	175	754
Indirect Inputs Emission								
Fertilizer	488	226	100	983	338	288	0	914
Feed Supplements	398	283	0	1000	623	149	487	911
Machinery	521	211	81	1261	495	178	302	747
Total Emission	1920	694	782	3867	2130	718	1416	3116

For an alternative, potentially better, evaluation of the environmental impacts of contrasting dairy farming systems, it is useful to evaluate their energy use and related carbon footprints on a milk production basis (Bos et al., 2014). Thus, in this study, carbon footprints of both dairy systems were also assessed based on their milk solids productions (Table 3-3). On average, the carbon footprints of pastoral (PDFs) and barn (BDFs) dairy systems per tonne of milk solids (t MS), were 1920 $kgCO_2\ tMS^{-1}$ and 2129 $kgCO_2\ tMS^{-1}$ respectively. The PDFs system displays 10% (209 $kgCO_2\ tMS^{-1}$) lower carbon footprints than the BDFs system during the production of one tonne of milk solids, indicating that the pastoral system is more environmentally friendly than the barn dairy system. Based upon the percentage input distribution of carbon footprints, a similar pattern was observed in the carbon footprint results of both systems (per tMS), as with the per hectare basis results.

In earlier literature, based on milk production, Saunders and Barber (2007) determined the carbon footprints for the NZ pastoral dairy system as 1371 $kgCO_2\ tMS^{-1}$. While Barber (2008) found carbon footprints for Lincoln University dairy farm as 1160 $kgCO_2\ tMS^{-1}$ based on milk production. When compared with the current study results, this indicates 28% and 39% growth in carbon footprints of NZ pastoral (PDFs) dairy system during the last decades, again suggesting an intensification trend for NZ pastoral dairy systems as a consequence of rising herd size and increasing energy use in the dairy farming systems. In another study, Latham (2010) developed a Canterbury model farm through a Ministry of Agriculture and Fisheries (MAF) pastoral modelling programme using energy data from previous studies (Saunders & Barber, 2007; Saunders et al., 2006) and found a carbon footprint of 1246 $kgCO_2\ tMS^{-1}$. The Latham (2010) carbon footprints for the Canterbury model farm is 35% lower than the carbon footprints observed in this current research study for PDFs system. However, the Barber (2008) and Latham (2010) results are inconsistent with previous NZ studies, probably due to using a different methodology approach, based around conversion of financial data into physical inputs and using only one set of farm data for the Canterbury model farm. This could not be considered as truly representative of all Canterbury region farms. However, all previous NZ studies, including this current research study, found that fertilizer (indirect input) and electricity (direct input) were the major energy inputs contributing significantly to carbon footprints of pastoral systems (PDFs). From a system comparative perspective, Flysjö et al. (2011) compared the NZ pastoral dairy system with the barn system from Sweden and found similar results to this study i.e. lower carbon footprints for NZ pastoral (PDFs) systems over the Sweden barn (BDFs) systems. In international literature, similar findings to this current research work were observed by O'Brien et al. (2012), where he found lower carbon footprints for Irish pastoral systems over the barn system, both per hectare and milk solids basis. Similarly to this study, he witnessed feed supplements and fertilizer among the leading energy inputs and main reasons for emission differences between the two systems. Therefore, it can be suggested that the pastoral system is potentially a more sustainable system than the barn one (based on energy carbon footprints) for the future of the NZ dairy industry.

3.3.2 Prediction of Carbon Footprints for NZ Dairy Farms

About carbon footprints prediction, a strong correlation between carbon footprints (CO_2) and energy based direct and indirect inputs were found. The results of the multiple linear regression model show the variables that can determine the carbon footprints (CO_2) of Canterbury dairy systems or farms (Table 3-4). The most accurate multiple linear model contained six variables: the total electricity used on the dairy farm during the year, the nitrogen (N) and sulphur (S) applied, feed supplement brought in for the season, the total number of effective milking hectares (Area) and whether the dairy farming system was pastoral or barn (DS). In the model, all the coefficients and overall model were statistically significant at 0.01 significance level.

The model showed that by increasing the consumption of electricity, nitrogen and sulphur fertilizers and imported feed supplements in the dairy system, the carbon emission ($CO_2\ ha^{-1}$) increases significantly. There is an inverse relationship between the number of effective hectares and carbon emissions as shown by the negative sign with the coefficient. Thus, increasing the effective milking hectare for dairy systems (farms) decreases the carbon emission significantly. The impact of dairy farming systems (PDFs or BDFs) contributed significantly to the carbon footprints of a dairy farm revealing that pastoral (PDFs) dairy systems were emitting less carbon dioxide (CO_2) compared to barn (BDFs) systems. Thus, PDFs could be considered as more sustainable dairy farming system in terms of carbon footprint for NZ dairy systems.

Table 3 - 4: Multiple Linear Regression Model for Carbon Emission of Dairy Systems

Variables	Unit	Coefficient (Std. Error)
Electricity Used	MegaWatt-hours/annum (MWh)	1.3* (0.2)
Nitrogen Consumption	Tonne/Annum (t/annum)	12.8* (3.5)
Sulphur Consumption	Tonne/Annum (t/annum)	19.0* (5.4)
Imported Feed Supplements	Tonne Dry Matter/Annum (tDM/annum)	0.9* (0.1)
Dairy Farming System	Pastoral=1 Barn=0	-321.9** (169.9)
Area	Eff. ha	-10.2 * (1.0)
Constant	-	3471.0* (194.7)

* p<0.01, ** p=0.01

This MLR model could explain the 85% and 93% variation in the dependent variable for training and validation data, repectively. The final root-mean-square error (RMSE) for the training and validation model were 333.4 $KgCO_2\ ha^{-1}$ and 294 $KgCO_2\ ha^{-1}$, respectively. A satisfactory regression model equation for carbon footprint (CO_2) estimation can be written as:

Carbon Footprint = 3471.0+ 1.3* Electricity + 12.8* N + *19.0** S + 0.9* Feed Supplement - 321.9* Dairy system (Pastoral/Barn) -10.2*Area (3-3)

The association between actual and predicted carbon emission ($KgCO_2\ ha^{-1}$) is given in Figure 3-2 and Figure 3-3, respectively.

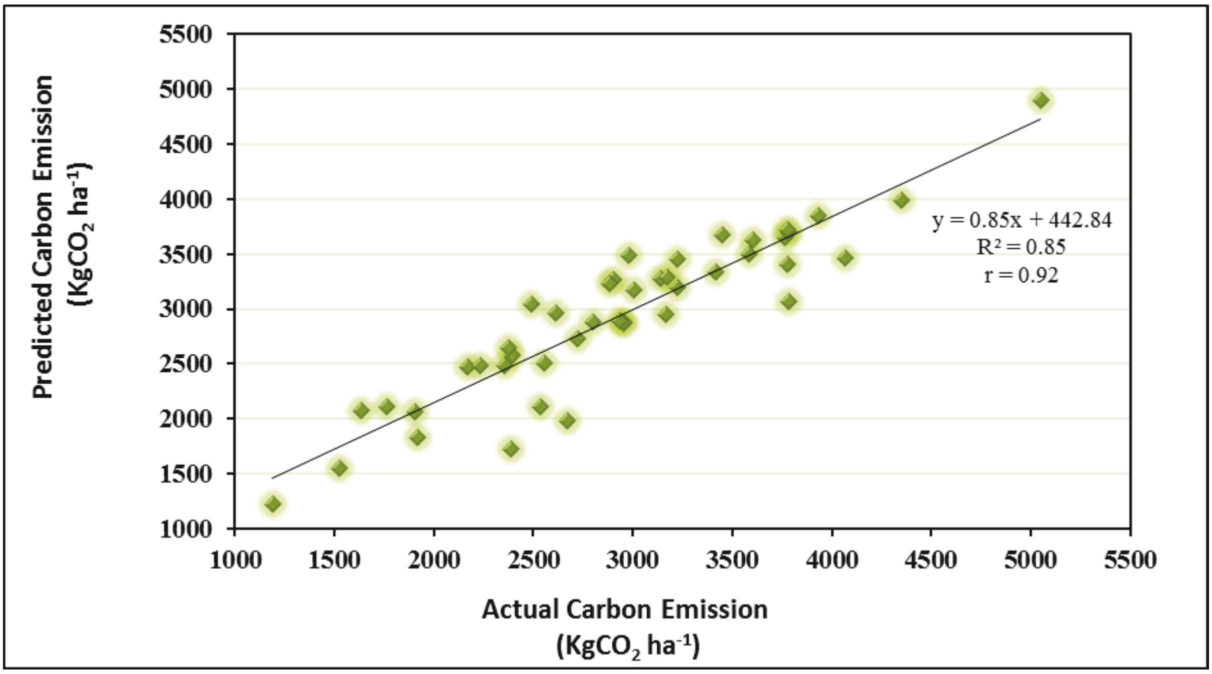

Figure 3 - 2: Correlation between Actual and Predicted Carbon Footprints through MLR for Training Data

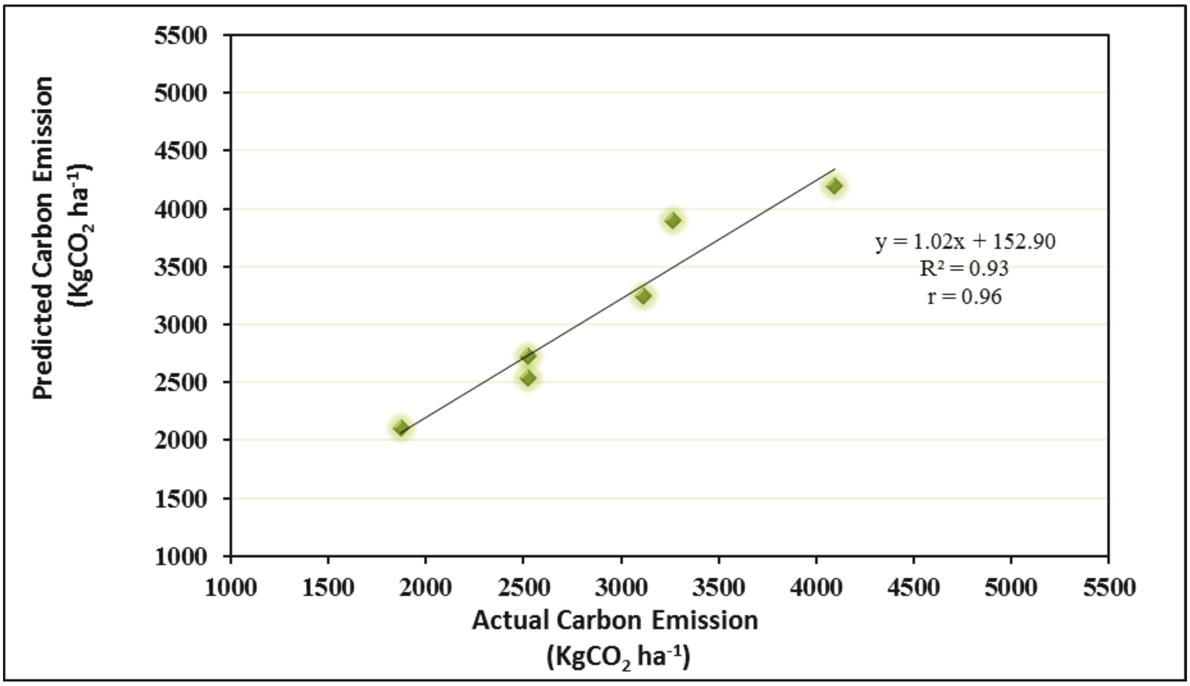

Figure 3 - 3: Correlation between Actual and Predicted Carbon Footprints through MLR for Validation Data

3.4 Discussion

Environmental sustainability is a topic whose importance has increased more and more in recent times. Moreover, the studies that directly compare energy related carbon footprints between PDFs and BDFs dairy systems are rare in New Zealand. In this context, this study provided a unique opportunity to researchers, stakeholders and policy makers to better understand the carbon footprints of contrasting dairy systems of New Zealand. Similarly, the knowledge about carbon footprints of NZ dairy systems is also needed, since it could improve the understanding about sustainable use of energy inputs (resources) to reduce the associated environmental emissions (CO_2). Thus, in this study, carbon footprints related to energy consumption of NZ pastoral (PDFs) and barn (BDFs) dairy systems were evaluated based on emissions from direct and indirect energy inputs. The results indicated that NZ pastoral (PDFs) dairy systems have 15% lower carbon footprints (per hectare basis) compared to barn dairy systems (BDFs). This indicates the intensive nature of the BDFs system over the PDFs system, meaning more energy inputs or resources are consumed in the barn system, which released more carbon emission (per hectare basis) compared to the pastoral system. Similarly, in terms of per unit of milk solids, the carbon footprints due to energy consumption are smaller in PDFs than the BDFs system. The main difference between carbon footprints of both systems is due to the type and amount of imported feed supplements, which are higher in the barn system due to higher stocking rate and longer lactation period. In respect to type of feed supplements, the barn system probably used more concentrated feed than the pastoral system. Off-farm, the production of these imported feed supplements released carbon dioxide (CO_2) emission into the atmosphere along with emissions from the manufacturing process of energy inputs (fertilizer, machinery etc.) consumed in the production process of feed supplements.

The other key difference between the carbon footprints of both systems is due to fertilizer consumption. This is comparatively low in the barn (BDFs) system due to better control on effluent collected under barn facilities. This is probably one of the main benefits of using the barn system, but high installation and operating cost along with dependence on a volatile milk price to make the system profitable may off-set the potential benefits (Newman & Journeaux, 2015). In addition to that, the use of barn facilities makes the dairy system more intensive, increasing stocking rate and inputs to produce more milk per cow. This in turn has increased cow size (weight) in the barn system, probably resulting in more methane emission per cow, as bigger cows produce more enteric methane due to their higher feed intake (Knapp, Laur, Vadas, Weiss, & Tricarico, 2014; Morais, Teixeira, Rodrigues, & Domingos, 2018). Based on these other greenhouse gases (CH_4, N_2O etc.) and environmental impacts, a number of worldwide studies have recommended the pastoral system as the ultimate solution to environmental challenges (such as climate change) rather than the barn system (A Greener World, 2013; Alan Rotz et al., 2009; O'Brien et al., 2014). Moreover, according to Newman and Journeaux (2015) study, it is difficult to achieve simultaneous environmental and financial benefits of the barn system. Under these situations, using barn facilities is probably not a good solution for NZ dairy systems both from environmental and financial perspectives since the volatile and unpredictable nature of NZ milk prices might put any investment in the barn system under risk.

Usually, the environmental loads of dairy farming systems are measured in the form of pollutants released during the product life cycle through considering on-farm direct emissions. Indirect emissions released off-farm during the production of materials used for manufacturing of indirect energy inputs (fertilizer, machinery and equipment) are rarely included. Murgia et al. (2013) and Todde et al. (2018a) estimated the carbon footprint of Italian dairy systems through considering only direct energy inputs. A limited number of other researchers (Todde et al., 2018b; Wells, 2001), however, have determined carbon footprints of dairy systems based on both direct and indirect energy inputs. In this context, the current research work, similar to other NZ research studies measured carbon footprints based on both direct and indirect energy inputs (Saunders et al., 2006; Wells, 2001). Likewise this current study, along with Saunders and Barber (2007) and Latham (2010) found the proportion of carbon footprints due to indirect energy inputs greater than the carbon footprints of direct energy inputs in the PDFs dairy system. The similar trend of higher carbon footprints due to indirect energy inputs was observed by Todde et al. (2018b). However, the Wells (2001) findings contradicted this, where a higher proportion of the carbon footprint belonged to direct energy inputs instead of indirect inputs.

From a comparative perspective, the energy related carbon footprints of pastoral (PDFs) and barn (BDFs) dairy systems are under-studied in New Zealand. However, there are a number of researchers who have assessed the carbon footprint from energy consumption in NZ pastoral dairy systems (Latham, 2010; Saunders et al., 2006; Wells, 2001). Likewise in this research work, they found electricity and fertilizer as major sources of carbon (CO_2) emissions among direct and indirect energy inputs in the pastoral system, which indicates that over the time, the use of electricity and fertilizer inputs intensified in NZ pastoral (PDFs) dairy systems, due to more use of irrigation and electrical equipment in milking sheds as well as high usage of fertilizer for growing more pasture to meet required feed demand, resulted in more energy consumption and related carbon emissions.

At present, energy management and environmental sustainability of farming systems are the topics whose importance has been increasing in recent times. In New Zealand, currently reducing environmental emissions from dairy farming systems is a critical issue for the NZ dairy industry. In this regard, minimizing carbon footprints associated with energy consumption will helpful to achieve New Zealand's emission reduction targets[12] and will also reduce overall GHG emissions from NZ dairy systems to have more climate friendly farming systems. Thus, a reduction in carbon footprints through better energy management or by improving energy efficiency would be beneficial and recommended for both dairy systems of New Zealand

3.5 Conclusion

Environmental sustainability and energy management of agricultural systems are topics whose importance has been increasing in recent times. Moreover, the studies that directly compare energy related carbon footprints between NZ pasture and barn dairy systems are under studied in New Zealand. In this context, the study carried out could provide a unique opportunity to researchers, stakeholders and policy makers to better understand carbon footprints of contrasting dairy systems of New Zealand. The findings of this study indicate that NZ pastoral (PDFs) dairy systems have lower carbon footprints both per hectare of farm land and per tonne of milk solids, compared to barn dairy systems (BDFs). On average, the carbon footprints of pastoral and barn dairy systems were 2857 kgCO_2 ha^{-1} and 3379 kgCO_2 ha^{-1}, and 1920 kgCO_2 tMS^{-1} and 2129 kgCO_2 tMS^{-1} respectively. The difference between the two systems indicates that the BDFs system has 18% and 11% higher carbon footprints than the PDFs system, both per hectare of farm area and per tonne of milk solids. The greater carbon footprints in the BDFs system was explained by higher use of energy inputs such as imported feed supplements, machinery and fossil fuels which released more carbon

[12] Under Paris Accord commitments, New Zealand's government proposed a "Zero Carbon Bill" which sets new emissions reduction targets for whole NZ industries including the dairy sector, such as carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions which have to reduce to net zero by 2050, while methane (CH_4) has a reduction target up to 10% by 2030 (DairyNZ, 2019).

emission (CO_2) compared to the PDFs system. Furthermore, a multiple linear model was developed which can predict carbon emission (CO_2) based on energy inputs (electricity, nitrogen and sulphur fertilizer and imported feed supplement), effective milking hectares and farm management system (PDFs/BDFs).

Chapter 4

Energy Efficiency Outlook of New Zealand Dairy Farming Systems: An Application of Data Envelopment Analysis (DEA) Approach[13]

Abstract

Energy efficiency is an important consideration for developing sustainable farming practices. The purpose of this study was to analyse energy efficiency of pastoral (PDFs) and barn (BDFs) dairy systems in New Zealand and find the optimal energy consumption for improving energy efficiency of both dairy systems through the data envelopment analysis (DEA) technique. In this study, two models constant return to scale (CCR) and variable return to scale (BCC) of DEA were employed for determining the technical (TE), pure technical (PTE) and scale (SE) efficiencies of pastoral (PDFs) and barn (BDFs) dairy systems. Further, benchmarking was performed to separate efficient and inefficient dairy farms and the energy saving potential was identified for both systems based upon optimal energy consumption. In this study, the average technical, pure technical and scale efficiencies of pastoral (PDFs) were 0.84, 0.90, 0.93 and for barn (BDFs) dairy systems were 0.78, 0.84, 0.92 respectively, indicating that energy efficiency is slightly better in PDFs system than the BDFs.

From the total number of dairy farms, 40% and 48% were efficient based on the constant return to scale and variable return to scale models respectively. Further, the energy saving potentials for PDFs and BDFs dairy systems through optimal energy consumption were identified as 23% and 35% respectively. The results of the optimal energy use calculated through DEA suggested that for pastoral (PDFs) dairy system electricity and fertilizers energy inputs have higher potential for energy savings, while in barn (BDFs) imported feed supplement and electricity have greater potential for energy savings through energy efficiency improvement. Thus, energy auditing and use of renewable energy resources were recommended for energy efficiency improvement in both dairy systems.

[13] This chapter has published in the Journal of "Energies". The main work was carried out by Hafiz such as concepts development, data collection, analysis and writing the manuscript. All co-authors provided feedback on development of the manuscript.

Keywords: Energy Efficiency, Data Envelopment Analysis (DEA), Pastoral Dairy Farming System (PDFs), Barn Dairy Farming System (BDFs)

4.1 Introduction

Energy consumption estimation in agriculture has been an essential tool in determining sustainable farming practices, with increased energy prices, strict environmental laws alongside end-use energy policies increasing the need for minimal and efficient energy consumption (Liang, Fan, & Wei, 2007; Mohammadi et al., 2014). Energy use efficiency is seen as an important condition for sustainability of farming systems with the potential to provide financial savings, preserve fossil fuel resources and reduce environmental impacts. It has been suggested that cost-efficient means to save energy and related emissions can decrease up to one third of worldwide energy demand by 2050 (Esengun, Gündüz, & Erdal, 2007; Lackner, 2017; Uhlin, 1998).

At present, increasing worldwide productivity and profitability ratios are the main concerns for farming systems and both depend on the magnitude of energy consumption. The energy used in agriculture including dairy farming systems depends on the amount of agricultural work performed, the land area used and the level of farm mechanization (Alam, Alam, & Islam, 2005; Todde et al., 2018b; Uzal, 2013). There are two reasons to improve energy efficiency of dairy farming systems: financial and environmental. From the financial perspective, energy usually costs money and from the environmental point of view, energy causes problems such as global warming, loss of biodiversity and contamination of water resources. In New Zealand, according to the Ministry for the Environment (2016) report, the agricultural sector alone produced 49% of New Zealand total greenhouse gas (GHG) emissions, with methane (CH_4) and nitrous oxide (N_2O) contributing around 72% and 21% of the emissions through enteric fermentation and agricultural soils respectively. It is subsequently argued that the emission of greenhouse gases has caused adverse weather conditions for livestock farming systems including dairy through affecting animal health, grazing, reproduction systems and ultimately creating sustainability challenges (Nardone, Ronchi, Lacetera, Ranieri, & Bernabucci, 2010). Hence, it is necessary for the dairy farming systems to consider their energy expenditure and improve energy efficiency in order to reduce energy consumption and associated environmental emissions.

To minimize greenhouse gas emissions requires a reduction in farm energy inputs (fossil fuels, fertilizer etc.). This goal can be achieved in two ways: either through achieving a substantial increase in energy efficiency where the same output is produced with less energy input, or through using more sustainable energy sources such as solar, wind, biomass etc. (Corré, Schröder, & Verhagen, 2003). According to Dalgaard, Halberg, and Porter (2001) and Meul et al. (2007), the development of energy efficient farming systems should help in reducing greenhouse gas emissions as well as providing financial benefits to farmers. For that purpose, knowledge related to energy efficiency and optimal energy consumption in different dairy farming systems is necessary.

To measure the efficiency of farming systems, two major techniques have been developed and used by researchers and scientists, the parametric (econometric modelling) and non-parametric (mathematical programming). In Nigeria, a parametric technique stochastic frontier production function (SFPF) was used for the evaluation of efficiency of food crop production (Ajibefun, Daramola, & Falusi, 2006). In another study, Moreira López and Bravo-Ureta (2009) employed a meta-regression analysis technique for the measurement of efficiency of Spanish and English dairy farms. Nassiri and Singh (2009) estimated efficiency of paddy crop farms through application of the non-parametric data envelopment analysis (DEA) technique. In New Zealand, a parametric technique such as stochastic frontier analysis (SFA) was employed to measure the efficiency of NZ dairy farms (Jaforullah & Devlin, 1996; Jiang, 2011; Jiang & Sharp, 2014). While Jaforullah and Whiteman (1999) and Wei (2014) used the non-parametric data envelopment analysis (DEA) method along with the stochastic frontier analysis (SFA) to evaluate efficiency performance of New Zealand dairy farms.

Data envelopment analysis is a non-parametric evaluation technique based on mathematical programming, which determines the relative efficiency of a number of decision making units (DMUs) (Adler, Friedman, & Sinuany-Stern, 2002). Two models CCR and BCC based on their authors' names Charnes, Cooper, and Rhodes (1978) and Banker, Charnes, and Cooper (1984) respectively, are commonly used in the DEA technique based on return to scale parameter. DEA has been recognized as a valuable method for determining relative energy efficiency of different dairy farming systems. DEA has many advantages, one advantage is that it does not require any prior assumptions on the underlying functional relationship between inputs and outputs (Seiford & Thrall, 1990).

Another advantage of DEA is that it allows researchers to consider multiple inputs and outputs concurrently, where efficiency of each DMU is compared to that of an ideal operating unit instead of average performer unit. Thus, the researchers can distinguish or separate efficient DMUs from inefficient ones and identify the amount and sources of inefficiency for each inefficient DMU (Angulo-Meza & Lins, 2002).

Due to the numerous benefits of DEA, a number of researchers have used this method in the dairy sector for efficiency evaluation. In Canada, Cloutier and Rowley (1993) compared efficiencies of 187 dairy farms between 1988-1989 and found larger farms were more efficient than the smaller ones. Barnes and Oglethorpe (2004) determined technical and cost efficiencies of 57 Scottish dairy farms and found low technical, cost and scale efficiencies, and thus recommended changes in farm size or scale. In NZ literature, Jaforullah and Whiteman (1999) applied DEA on NZ dairy farms and found average scale efficiency around 94% and more than half of the dairy farms operating below the optimal scale. Using the same data set, Jaforullah and Premachandra (2003) recognized that the technical efficiencies of individual dairy farms were sensitive to the choice of production frontier estimation method such as SFA and DEA. In another study, Wei (2014) determined the technical efficiency performance of NZ dairy farms through combined application of DEA and stochastic frontier analysis (SFA) techniques for the season 2006-07 and compared efficiency results received with these two methods. He found average technical efficiency was around 96% in SFA and 82% and 86% in DEA under constant and variable return to scale models respectively.

The dairy industry is one of the important and influential agricultural sectors of New Zealand. Dairying is a significant contributor to the New Zealand economy and ranks first amongst other agricultural export earners through generating a revenue around NZ$ 13.6 billion in 2016 (Ballingall & Pambudi, 2017). The New Zealand dairy industry is renowned for its low input and efficient pasture based dairy system (PDFs). However, the intensification of this pasture based dairy system over the last decades, as well as rising sustainability concerns due to the challenges of nutrient leaching and greenhouse gas emissions is of concern to many. One response to these challenges has been the introduction of the barn dairy system (BDFs) into New Zealand, in which animal shelter (the barn) is used in combination with pasture grazing for the purposes of reducing soil damage, animal lameness and environmental impacts (Pow et al., 2014). For milk production, both dairy systems PDFs and BDFs, use energy in both direct and indirect forms. Direct energy is the energy which is directly measureable and is mainly derived from diesel, petrol and electricity used in agricultural activities whilst indirect energy is the energy used to produce other farm inputs such as feed supplements, fertilizer and machinery etc. Thus, the total energy use in farming systems comprises all of the energy used either directly or indirectly until the milk leaves the farm gate (Meul et al., 2007).

In international literature, there are several studies that have evaluated energy efficiency of dairy farming systems. For example, Uzal (2013) compared energy efficiency of dairy farming systems with different housing structures (freestall, loose housing) and found the freestall dairy system more efficient compared to other systems. Meul et al. (2007) studied the changes in energy use efficiency of Flanders dairy farms over different time periods and found a decreasing trend in energy use over the considered time period, due to increasing energy productivity of considered dairy farms. Sefeedpari (2012) applied the DEA technique to calculate the energy efficiency of Iranian dairy farms and found 51% farmers efficiently using their energy inputs. While in another study, Hosseinzadeh-Bandbafha et al. (2018) employed the DEA approach to determine the energy efficiency and energy saving targets for Iranian dairy farms and recognized feed intake and fossil fuels were the leading energy saving inputs for Iranian dairy farms.

From the NZ viewpoint, a number of researchers estimated the energy consumption of dairy farming systems (Latham, 2010; McChesney, Sharp, & Hayward, 1981; Podstolski, 2015; Saunders & Barber, 2007; Wells, 2001), but gave very little consideration to energy efficiency. However, Wells (2001) and Podstolski (2015) determined overall energy ratio[14] (OER) for NZ PDFs systems as an energy efficiency indicator. From a systems comparative perspective, there is not a single study in NZ literature which has compared energy efficiency of pastoral (PDFs) and barn (BDFs) dairy farming systems using the DEA technique. In this context, this is perhaps the first study in NZ, which evaluates energy efficiency of contrasting dairy systems of NZ through DEA application.

[14] Overall Energy Ratio (OER): is the ratio of total energy input to the total energy output of the product. This is the inverse of energy efficiency and used as an energy efficiency indicator.

Thus, in this study, the DEA technique was employed for evaluation of energy efficiency of PDFs and BDFs systems. Further, benchmarking was performed to separate efficient and inefficient dairy farms, and optimal energy consumption was determined for inefficient dairy farms in order to identify potential energy savings from different energy sources.

4.2 Materials and Methods

4.2.1 Data Collection and Processing

The present study was carried out in the Canterbury province of New Zealand. In this study, 50 dairy farms were selected from Canterbury including 43 pastoral (PDFs) and 7 barn farms (BDFs). The primary data for the season 2016-17 were collected from dairy farmers through a survey questionnaire and face-to-face interview method. The questionnaire was designed to collect the information related to various inputs including diesel, electricity, fertilizer, total working hours of labour, total working hours of machinery etc. This study only considered cradle-to-farm gate energy inputs that were used for the production of milk up to the farm gate, i.e. transport and post-processing components were not considered.

Each input recorded in the questionnaire was then converted into an energy equivalent by using their appropriate energy equivalent factors. Table 2-1 in Chapter 2 shows the values of energy equivalents for inputs used in both PDFs and BDFs systems. In this study, energy inputs comprised fossil fuels, electricity, human labour, feed supplements, fertilizer and machinery while milk production was considered as the output energy. The total energy input estimated was the sum of the input factors multiplied with the appropriate energy conversion coefficient for each factor (Kazemi, Shahbyki, & Baghbani, 2015).

Energy inputs are also classified as direct and indirect energy forms (Wells, 2001). In this study, direct energy encompassed diesel, petrol, electricity, human labour while indirect energy involved fertilizer, imported feed supplements and machinery used in the dairy farming operations. In addition to energy efficiency of both dairy systems, energy indicators were also determined in this study, through equations 4-1 and 4-2 (Jekayinfa & Bamgboye, 2008; Meul et al., 2007; Podstolski, 2015; Uzal, 2013):

$$\text{Energy Productivity (EP)} = \frac{\text{Milk Output (tMS ha}^{-1}\text{)}}{\text{Energy Input (MJ ha}^{-1}\text{)}} \qquad (4\text{-}1)$$

$$\text{Overall Energy Ratio (OER)} = \frac{\text{Energy Input (MJ ha}^{-1})}{\text{Energy Output (MJ ha}^{-1})} \tag{4-2}$$

Where, 'EP' is energy productivity (tMS MJ^{-1}), 'OER' is the overall energy ratio "the ratio of total energy input to the total energy output of the product". OER describes an inverse of energy efficiency, a higher OER means lower efficiency and vice versa.

4.2.2 Data Envelopment Analysis Approach

Data envelopment analysis (DEA) is a technique used for the assessment of non-parametric efficiency frontiers in multi-factor production analysis. DEA uses linear programming to form a non-parametric frontier above the data, which serves as relative benchmark for evaluation of efficiency among other homogenous decision-making units (DMUs) under analysis (Alzamora & Apiolaza, 2013; Coelli et al., 2005). Data envelopment analysis allows each DMU to choose any combination of inputs and outputs to maximize its relative efficiency. The relative efficiency score of a decision-making unit (DMUs) is defined as a ratio of weighted sum of outputs to weighted sum of inputs. This relative efficiency score is a non-negative value based on the linear relationship between inputs and outputs (Zhu, 2014). Assume 'n' DMUs are to be assessed, each using different combination of 'r' outputs and 's' inputs. The objective function of DMU 'd' in the set of 'j' DMUs (j =1,2, 3..., n) can be written as equation 4-3:

$$\text{Maximizing Efficiency}_d = \frac{\sum_{r=1}^{p} u_r y_{rd}}{\sum_{s=1}^{q} v_s x_{sd}} \tag{4-3}$$

Subject to $\frac{\sum_{r=1}^{p} u_r y_{rj}}{\sum_{s=1}^{q} v_s x_{sj}} \leq 1$, for j =1,2, 3..., n

u_r and $v_s \geq 0$, r = 1, 2, 3,….., p and s = 1, 2, 3..., q.

whereas 'y_{rd}'is the amount of output (r) produced by DMU 'd' , 'x_{sd}'is the amount of input (s) consumed by DMU 'd', 'y_{rj}'is the amount of output (r) produced by DMU 'j' , 'x_{sj}'is the amount of input (s) consumed by DMU 'j' and 'u_r' and 'v_s' are the weight given to individual output and input (Allen & Thanassoulis, 2004).

Charnes et al. (1978) introduced the CCR model based on the assumption of constant return to scale (CRS), which implies that an input increase will result in a proportional output increase. In the CCR model, the efficiency frontier is a straight line which intersects the origin point and best performing unit(s) as shown in Figure 4-1. The best performing unit is the one with the highest output to input ratio, in Figure 4-1 this is P_2. This point thus serves as a reference DMU to all other units under investigation. The CCR model allows the identification of inefficient DMUs with consideration of scale size. In CCR models, both technical and scales efficiencies are present, which are based on input/output arrangement (management techniques) and scale size. The efficiency measured under the CRS assumption is the technical efficiency.

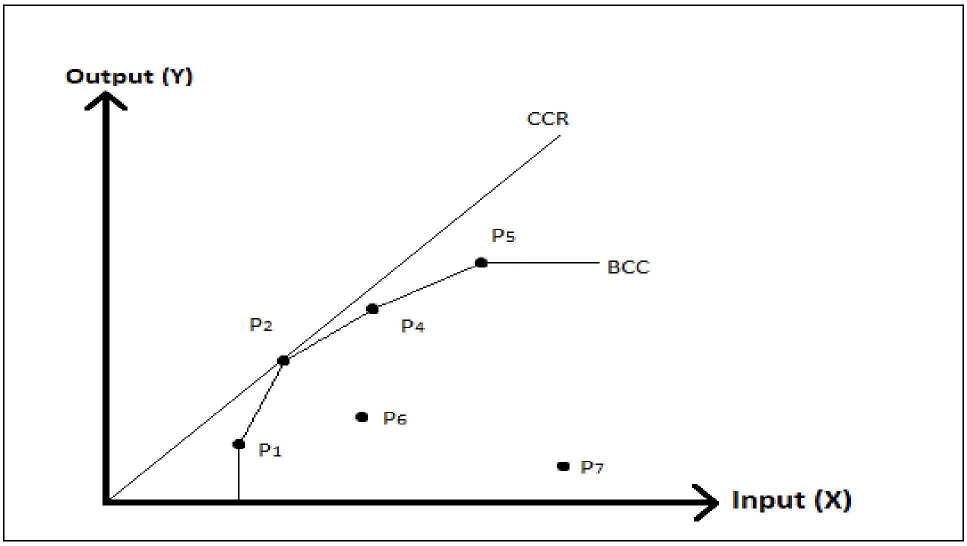

Figure 4 - 1: Efficiency Frontiers based on CCR and BCC models

Banker et al. (1984) presented the BCC model based on the assumption of variable returns to scale (VRS), which implies that an input increase will result in a non-proportional output increase. In the BCC model, the efficiency frontier changed from a straight line to a convex structure. This convex combination of the efficient DMUs serves as reference point for other inefficient units. In Figure 4-1, the BCC model shows more than one efficient DMU on the frontier line (P1, P2, P4, P5) using the same DMUs as in the CCR model. The BCC model has few advantages over the CCR model. The BCC model frontier envelops more data so has more efficient units than CCR and the efficiency scores of BCC model are higher or equal to those of CCR as it connects the outermost DMUs (including the one determined efficient by CCR). Due to the presence of more than one efficient DMUs in the model, the inefficient units under the BCC model get the opportunity to be compared with more appropriate efficient units (Zhu, 2014).

The pure technical efficiency (PTE) is defined as the technical efficiency of DMUs measured under variable return to scale assumption. The BCC model also known as the VRS model, gives the pure technical efficiency of DMUs without consideration of scale size. In simple words, the CCR model efficiency is the combination of technical efficiency (TE) and scale efficiency (SE), while the BCC model separates the TE and SE and measures pure technical efficiency (PTE).

Scale efficiency (SE) captures the effect of scale size on the efficiency of DMU and indicates that some portion of inefficiency belongs to the inappropriate size of a DMU. The efficiency score variation between CRS and VRS models is captured in scale efficiency. The relationship between technical (TE), pure technical efficiency (PTE) and scale efficiency (SE) can be explained as follows (Chauhan, Mohapatra, & Pandey, 2006; Nassiri & Singh, 2009):

$$\text{Scale efficiency} = \frac{\text{Technical Efficiency}}{\text{Pure Technical Efficiency}} \tag{4-4}$$

In DEA application, the efficiency of a unit can be attained either by input or output orientation. In input orientation models, efficiency is attained by minimizing input usage while maintaining the same output levels, whereas output orientation models focus on increasing output levels while maintaining the same level of inputs. Here, an input-oriented DEA approach was adopted for the efficiency measurement of dairy farms. This orientation is considered more suitable for agriculture as farmers have more control over input usage compared to output, which is often influenced by exogenous factors (rain, soil structure, climate etc.). Likewise, this orientation choice is in accordance with the current situation of New Zealand dairy farming systems, where more focus is on efficient input usage (due to environmental issues) rather than productional increase. In this study, the decision-making units (DMUs) are the dairy farms (PDFs & BDFs), while direct and indirect farm inputs were considered as energy inputs in mega joule per hectare (MJ ha^{-1}) and milk energy per hectare(MJ ha^{-1}) was considered as the output energy for the individual DMU or dairy farm.

To measure the efficiencies of selected DMUs (dairy farms) based on CCR and BCC models, the Data Envelopment Analysis Program (DEAP) software version 2.1 was employed (Coelli, 1996; Coelli et al., 2005). The focus was to determine the optimal energy input efficiency with consideration of the input/output management and scale size of different dairy farming systems (PDFs & BDFs), so further analysis was based on the CCR model.

The DEA divides the DMUs (dairy farms) into efficient and inefficient sets; the inefficient DMUs are ranked on their efficiency scores; while DEA lacks distinction between efficient DMUs. Thus, to rank efficient DMUs, a benchmarking method was employed, the efficient unit is ranked higher which is chosen as a relative peer by many inefficient DMUs, and frequently appears in the reference set.

4.3 Results

4.3.1 Energy Use Pattern

The amount of energy inputs for pastoral (PDFs) and barn (BDFs) dairy systems are summarized in Chapter 2. The total energy used in each dairy system contained energy generated from direct and indirect inputs. According to the results, on average PDFs and BDFs dairy systems used energy as 50,538 $MJha^{-1}$ and 55,833 $MJha^{-1}$ respectively. The difference in total energy input of both systems is 5,295 $MJha^{-1}$ indicating 9.5% less energy consumption in the PDFs system. In comparison to previous NZ studies (Latham, 2010; Saunders & Barber, 2007; Wells, 2001), energy use in the PDFs system has increased as consequences of dairy intensification.

Considering total energy consumption in terms of its component parts revealed that electricity (35.5%) and fertilizer (29.9%) consumed most energy in pastoral dairy systems (PDFs), followed by machinery (15.7%) and feed supplements (14.1%). However in contrast to PDFs, total energy consumption of BDFs systems indicates that most energy was consumed in electricity (34.8%), followed by imported feed supplement (24.1%) and fertilizer (16.5%). The highest share of electricity among total energy consumption indicates high consumption of electricity in irrigation and dairy shed operations.

4.3.2 Identification of Efficient and Inefficient Dairy Farms

The frequency wise distribution and summary of efficiency scores (TE, PTE & SE) of 50 dairy farms (DMUs) are presented in Figure 4-2 and Table 4-1. The technical and pure technical efficiencies were based on the CCR and BCC models of the DEA respectively.

The results of the input-oriented CCR model shows that out of 50 dairy farms (DMUs), only 20 dairy farms or DMUs (40%) were efficient, revealing that the majority of the dairy farms (60%) can improve their energy inputs utilization. Moreover, the average technical efficiency score of the inefficient 30 dairy farms (DMUs) was 0.72, implying that they can save energy and reach efficiency by reducing energy inputs usage from different sources by up to 28%.

The results of the input-oriented BCC model of DEA showed that more dairy farms (DMUs) were efficient compared to the CCR model, as explained in Figure 4-2. Based on pure technical efficiency, 24 dairy farms or DMUs (48%) were now efficient including the DMUs 5, 9, 20 and 37 (which were inefficient in the CCR model application).

From a systems perspective, the average technical efficiency score for pastoral dairy systems (PDFs) was 0.84, ranging from 0.36-1 with a standard deviation of 0.19, whereas for barn dairy systems (BDFs), TE was 0.78 with a standard deviation of 0.20 and ranging from 0.51-1. The result indicates that energy efficiency of pastoral dairy systems (PDFs) is slightly better than the energy efficiency of barn systems (BDFs). The average of pure technical efficiency of the PDFs system was 0.90 ranging from 0.58-1, while for the BDFs system it was 0.84 ranging from 0.55 to 1.

Table 4 - 1: Technical, pure technical and scale efficiencies of PDFs and BDFs (50 DMUs)

	Pastoral				Barn			
Particular	**Avg**	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
Technical Efficiency	0.84	0.19	0.36	1.00	0.78	0.20	0.51	1.00
Pure Technical Efficiency	0.90	0.13	0.58	1.00	0.84	0.18	0.55	1.00
Scale Efficiency	0.93	0.11	0.57	1.00	0.92	0.07	0.81	1.00

Among pastoral farms, the number of least inefficient farms (scores between 0.70 and 0.99) were 14 (58%) and 16 (59%) farms based on technical and pure technical efficiency scores respectively, Similarly among barn farms, a total of 3 (50%) and 3 farms (60%) were least inefficient based on technical and pure technical efficiencies, respectively (as shown in Figure 4-2). These dairy units have great potential to become efficient as their scores are nearer to reaching efficiency.

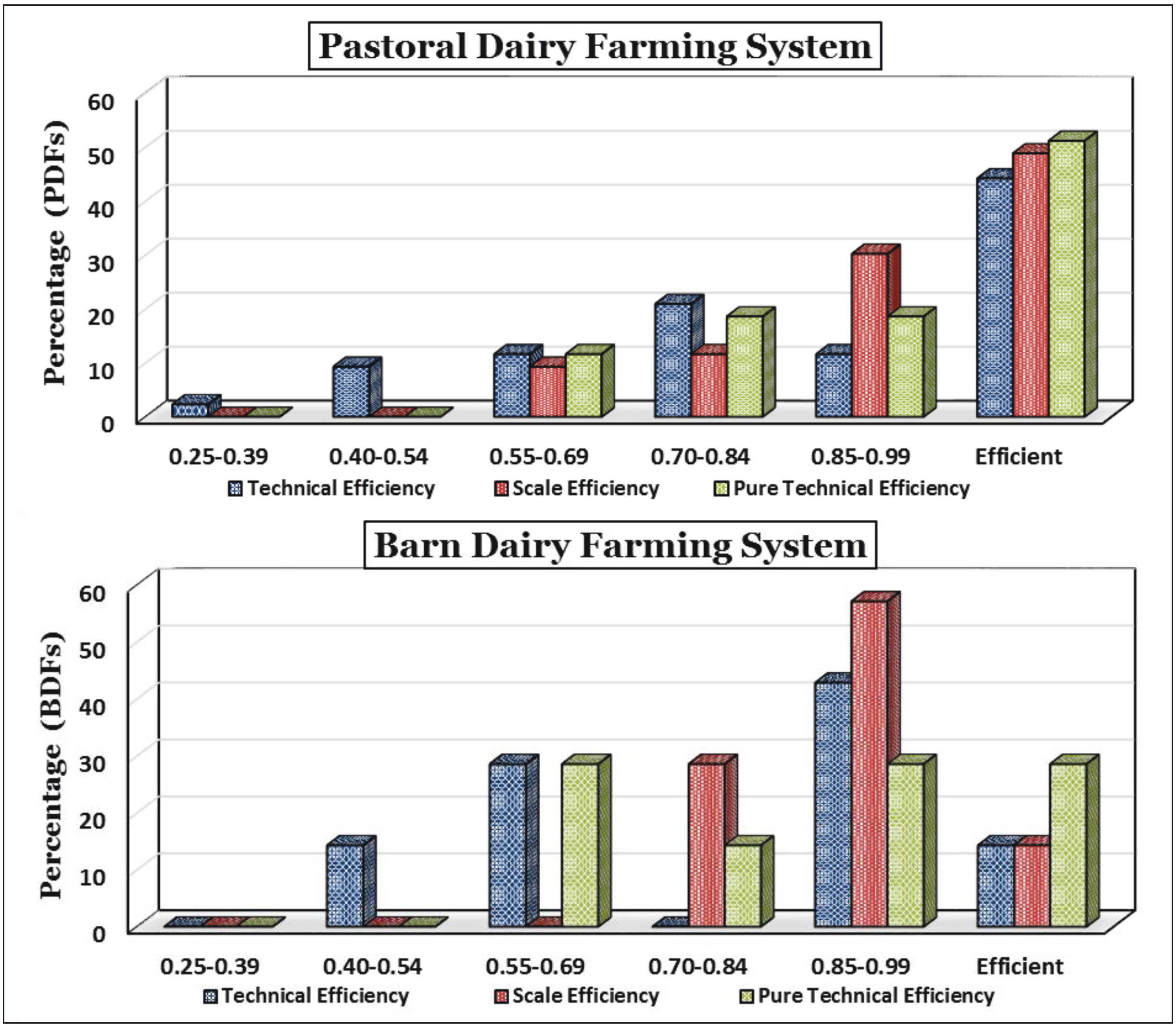

Figure 4 - 2: Efficiency Score of Pastoral (PDFs) & Barn Dairy Farming Systems (BDFs)

4.3.3 Benchmarking Categorization

DEA determines the relative efficiency of DMUs (dairy farms); meaning it ranks (weights) other DMUs according to the highly efficient DMU. The highly efficient DMU thus serves as the reference for the other units. This study applied the benchmarking technique for categorization of the DMUs (dairy farms). Benchmarking categorization allows us to identify the most appropriate (efficient) units by assessment and comparison with other units performing similar functions (Adler et al., 2002; Keehley, 1997). In Benchmarking, the efficient DMUs (dairy farm) which appear most in the referent set are considered superior and achieve a higher rank than the others. This identification and ranking can then help to identify the improvements in practices that may help in the attainment of higher performance. The efficiency benchmarking categorization of the 50 dairy farms (DMUs) including PDFs and BDFs dairy systems is given in Table 4-2.

Table 4 - 2: Benchmarking Results of Technical Efficiency Analysis

DMU	System	TE Score	Frequency in Referent set	Benchmarking[15]
1	P	1	9	
2	P	1	10	
3	P	1	10	
4	P	1	11	
5	P	0.68		1 (0.2) 2 (0.2) 6 (0.1)
6	P	1	7	
7	P	1	8	
8	P	0.36		2 (0.2) 3 (0.0) 4 (0.0) 6 (0.1) 14 (0.0) 23 (0.1)
9	P	0.98		1 (0.6)
10	P	1	2	
11	P	0.54		2 (0.1) 3 (0.1) 27 (0.0) 28 (0.2) **33 (0.1)** 49 (0.1)
12	P	0.81		4 (0.1) 28 (0.3) **33 (0.4)**
13	P	1	2	
14	P	1	2	
15	P	1	0	
16	P	1	3	
17	P	0.52		2 (0.2) 3 (0.0) 6 (0.4) 14 (0.0) 36 (0.0)
18	B	0.56		2 (0.1) 3 (0.0) 7 (0.1) 27 (0.3) **33 (0.1)** 36 (0.1)
19	B	0.63		1 (0.2) 13 (0.3) 27 (0.1)
20	B	0.94		3 (0.3) 4 (0.0) 28 (0.3) **33 (0.1)**
21	B	0.90		7 (0.7) 27 (0.2) 28 (0.0)
22	B	0.91		7 (0.6) 13 (0.0) 27 (0.2)
23	P	1	2	
24	P	0.97		2 (0.6) 4 (0.0) 6 (0.1) **33 (0.1)** 43 (0.3) 49 (0.0)
25	B	0.51		1 (0.2) 4 (0.1) 43 (0.0) 49 (0.3) 50 (0.2)
26	P	0.56		1 (0.1) 2 (0.1) 4 (0.1) 6 (0.4) 49 (0.0) 50 (0.1)
27	B	1	9	
28	P	1	9	
29	P	0.93		2 (0.2) 3 (0.3) 27 (0.0) **33 (0.3)** 36 (0.1)
30	P	0.69		4 (0.1) 6 (0.5) 43 (0.1) 49 (0.2)
31	P	0.70		3 (0.3) 28 (0.2) **33 (0.3)** 36 (0.1) 49 (0.1)
32	P	0.53		6 (0.1) 16 (0.5) 36 (0.1)
33	**P**	**1**	**13**	
34	P	0.76		1 (0.3) 16 (0.4) 36 (0.1)
35	P	0.71		2 (0.1) 3 (0.1) 27 (0.1) **33 (0.3)** 36 (0.0)
36	P	1	11	
37	P	0.92		7 (0.4) 28 (0.3) 43 (0.1) 49 (0.4)

[15] To simplify, the benchmarking composite units for DMU#5 are expressed as 1 (0.2) 2 (0.2) 6 (0.1), whereas 1, 2 and 6 are DMU numbers (which are efficient) and values in parenthesis represents the intensity vectors of the respective DMU's. The intensify vector indicates that the inputs usage and output production of the DMU#5 (inefficient unit) is closer to DMU# 1, 2 & 6 compared to other DMUs. By using benchmarked DMUs and intensity vector, the optimum energy requirement for the inefficient DMU#5 can be worked out to attain efficiency.

38	P	0.91		3 (0.2) 10 (0.1) **33 (0.3)** 36 (0.3) 40 (0.2)
39	P	0.56		3 (0.1) 7 (0.2) 27 (0.0) 28 (0.0) **33 (0.2)** 36 (0.0)
40	P	1	1	
41	P	0.66		1 (1.0)
42	P	0.81		1 (0.3) 4 (0.1) 43 (0.3) 49 (0.3)
43	P	1	6	
44	P	0.53		7 (0.5) 27 (0.1) 28 (0.1) 49 (0.0)
45	P	0.79		2 (0.2) 4 (0.3) 10 (0.0) **33 (0.2)**
46	P	0.70		1 (0.0) 4 (0.4) 23 (0.3) **33 (0.0)** 36 (0.0) 43 (0.1)
47	P	0.70		7 (0.0) 16 (0.1) **33 (0.6)** 36 (0.0)
48	P	0.74		4 (0.0) 7 (0.7) 28 (0.0)
49	P	1	9	
50	P	1	2	

The benchmarking categorization shows that the DMU#33 emerges as the most efficient DMU (dairy farm) by appearing in the benchmark referent set of the majority of the inefficient DMUs. The dairy farm representing the DMU#33 tops the ranking by 13 repetitions. This efficient DMU and other efficient units close to this can serve as appropriate efficient units for the inefficient DMUs. This implies that an inefficient unit (dairy farm) can improve energy use efficiency by following this composite set of efficient units rather than just following a single unit as benchmark. For instance, it can be said that DMU#5 should follow the practices of composite DMUs 1, 2 and 6 to achieve energy efficiency because the DMU#5 is closest to the efficiency frontier of these efficient DMUs.

Thus, the inefficient dairy farms can identify the reasons and make changes in their energy consumption by comparing themselves with the efficient dairy farms to acquire best energy management practices, which eventually will be leading energy efficiency and hence reduce energy consumption and associated carbon footprints (CO_2).

4.3.4 Optimal Energy Requirements and Energy Saving Capacity

The optimal energy requirements and energy saving capacity for the inefficient pastoral and barn dairy systems are summarized in Table 4-3, based on the CCR model. The results revealed that total optimal energy required for PDFs systems was 38,964 MJ ha^{-1} (actual energy used 50,538 MJha^{-1}), whereas for BDFs systems the optimal energy required was 36,469 MJ ha^{-1} (actual energy used 55,833 MJha^{-1}). The difference indicates inefficient use of energy inputs in both dairy systems. It is evident from the results that there is potential for a total of 11,574 MJha^{-1} of energy that could be saved by pastoral dairy farms, whereas for barn dairy farms it was 19,364 MJha^{-1} by efficient utilization of energy inputs while keeping the output unchanged.

Table 4 - 3: Optimal Energy Requirements & Energy Savings Capacity for both Dairy Systems

Inputs	Actual Energy Consumption (MJ ha^{-1})		Optimal Energy Requirements (MJ ha^{-1})		Saving Energy (MJha^{-1})	
	Pastoral	Barn	Pastoral	Barn	Pastoral	Barn
Diesel	1824	5099	1278	1782	546	3317
Petrol	687	1178	537	633	150	544
Electricity	17917	19447	14173	14586	3745	4861
Labour	86	114	70	79	15	36
Fertilizer	15128	9206	11975	6766	3153	2440
Feed Supplements	6937	12515	4491	6422	2446	6093
Machinery	7959	8274	6440	6201	1519	2073
Total	50538	55833	38964	36469	11574	19364

The distribution of the various energy inputs based on total energy saving potential for both pastoral (PDFs) and barn (BDFs) dairy systems is illustrated in Figure 4-3. Evidently, the highest energy saving contribution was from electricity (32.4%), followed by fertilizer (27.2%) and feed supplements (21.1%) for the pastoral dairy system (PDFs). While for the barn dairy system (BDFs), imported feed supplement (31.5%) contributed the major portion, followed by electricity (25.1%) and diesel (17.1%) for energy savings.

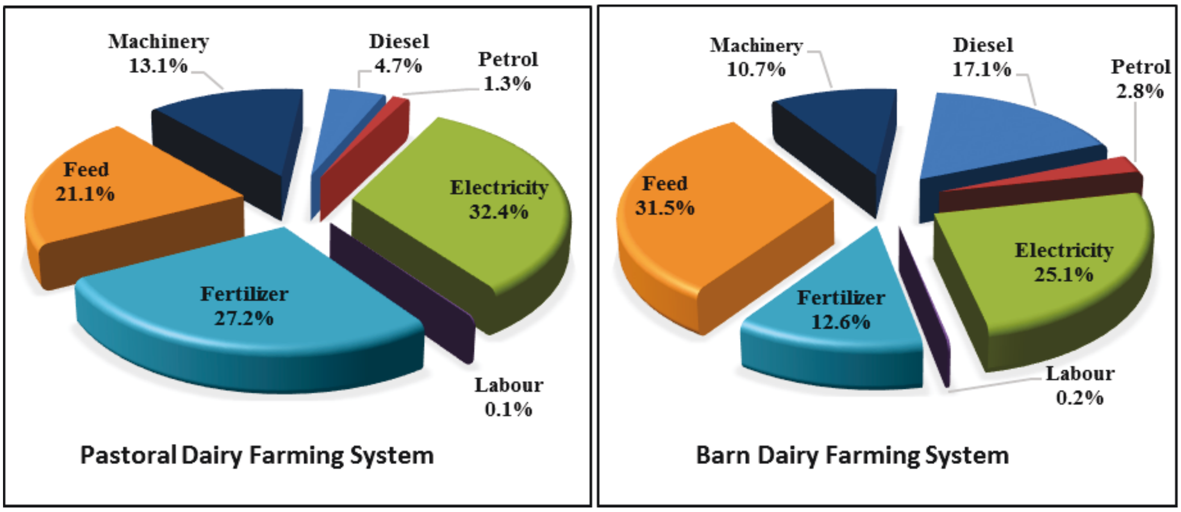

Figure 4 - 3: Percentage Distribution of Energy Savings Potential for PDFs and BDFs

4.3.5 Improvement of Energy Indicators

Energy indicators calculated for pastoral (PDFs) and barn (BDFs) dairy systems with actual and optimal energy consumption are presented in Table 4-4. Energy productivity rates based on actual and optimal energy consumption were found as 0.035 kgMS MJ^{-1} and 0.046 kgMS MJ^{-1}, and 0.031 kgMS MJ^{-1} and 0.048 kgMS MJ^{-1} for PDFs and BDFs dairy systems respectively, showing an improvement of 31% and 55% can be made in energy productivity of both pastoral and barn dairy systems respectively. The overall energy ratio (OER) based on optimal energy use were computed as 0.66 and 0.57 for PDFs and BDFs systems respectively. Thus, the results shows that compared with actual energy use in pastoral and barn dairy systems, OER can be improved by 27% and 38% with usage of suggested optimal energy requirements estimated by using the DEA method. In other words, the overall energy ratio (OER) would decrease from 0.90 to 0.66 for pastoral and 0.92 to 0.57 for barn dairy systems, when farmers of both dairy systems move from actual energy consumption to optimal energy requirements. This indicates that improvements in energy consumption can occur for both systems, however the OER results indicate that energy efficiency of pastoral systems was slightly better than the barn systems. However, when comparing OER results of PDFs systems with previous NZ studies, it showed an arbitrary trend as reported by different researchers McChesney et al. (1981) as 0.57, Wells (2001) as 0.99, Latham (2010) as 0.65 and Podstolski (2015) as 0.91. But over the decades, it is clear that OER has increased in the pastoral system which means energy efficiency has decreased over the previous years (as OER reverse of energy efficiency). Thus, energy efficiency improvements are necessary for NZ dairy farming systems to retain their competitive advantage of energy efficiency over their counterpart dairy industries, such as those in the European Union.

Table 4 - 4: Energy Indicators Improvement for NZ PDFs and BDFs Dairy Systems

Items	Unit	Actual Energy Consumption		Optimal Energy Requirement	
		Pastoral	**Barn**	**Pastoral**	**Barn**
Energy Productivity	kgMS MJ^{-1}	0.035	0.031	0.046	0.048
Overall Energy Ratio	MJ_{in}/MJ_{out}	0.90	0.92	0.66	0.57
Direct Energy	$MJha^{-1}$	20514	25838	16058	17080
Indirect Energy	$MJha^{-1}$	30024	29995	22906	19389

Further, with optimal energy consumption, the percentage reduction in direct and indirect energies was found as 22% & 24% in PDFs, and 34% & 35% in BDFs systems respectively. Thus, applying the DEA method for energy optimization can save the energy resources for both pastoral and barn dairy systems. In the literature, Hosseinzadeh-Bandbafha et al.

(2018) applied DEA on Iranian dairy farms and found that through optimization of energy consumption, energy indices such as energy efficiency and productivity can be improved by 12% in comparison with actual energy consumption on dairy farms. Potentially, NZ dairy farmers are unaware of the optimal energy use for their production output, thus farmers need to emphasis better energy management by using the latest and most efficient technology together with renewable energy resources to get optimal energy consumption. Overall, the application of the DEA model suggests that energy efficiency improvements are possible in both pastoral (PDFs) and barn (BDFs) dairy systems, which would help to reduce energy consumption and related environmental footprints and also provide financial benefits to farmers through cutting their energy cost. Hence, for energy efficiency improvement in both dairy systems, especially for inefficient dairy farms energy auditing and use of renewable energy sources were recommended to achieve sustainable and environmentally friendly dairy systems for the NZ dairy industry.

4.4 Conclusion

Dairy farming systems with better energy efficiency would help to reduce energy costs and environmental footprints, along with improving the productivity and profitability of farming systems. The main purpose of this study was to analyse the energy efficiency of NZ pastoral (PDFs) and barn (BDFs) dairy systems and find optimal energy consumption for increasing their energy efficiency through the data envelopment analysis (DEA) approach. The DEA models including input oriented CCR and BCC were applied to examine the energy efficiency of 50 dairy farms (DMUs) including PDFs and BDFs dairy systems. The average technical, pure technical and scale efficiencies of pastoral and barn dairy systems were 0.84, 0.90, 0.93 and 0.78, 0.84, 0.92 respectively, indicating that energy efficiency is slightly better in PDFs compared to BDFs systems. Based on CCR and BCC models, 20 and 24 dairy farms respectively out of 50 selected farms were efficient, indicating that the majority of farms were not technically efficient probably due to consuming higher energy inputs. Thus, inefficient farmers should pay attention to their consumption of energy inputs such as electricity, fertilizer and imported feed supplements as they have higher potential for energy savings. From a systems perspective, when comparing actual and optimal energy use of pastoral (PDFs) and barn (BDFs) dairy systems, results shows that 23% and 35% energy can be saved in both dairy systems respectively, with efficient or optimal energy consumption. Thus, for energy efficiency improvement in both dairy systems, especially for inefficient dairy farms energy auditing and use of more renewable energy sources were recommended to achieve sustainable and environmentally friendly dairy systems for the NZ dairy industry.

Chapter 5

Overall Conclusions

5.1 Overview

The dairy farming industry is a significant contributor to the New Zealand economy, generating NZ$ 13.6 billion in 2016 (Ballingall & Pambudi, 2017). At present, NZ dairy farming systems are under high scrutiny and facing huge public pressure due to their high utilization of energy inputs and related environmental impacts (nutrient leaching into waterways, GHG emissions). Currently, reducing greenhouse gas emissions from NZ dairy systems is a critical challenge for the NZ dairy industry in achieving a future sustainable dairy system. In this context, identification of dairy farming systems with efficient energy consumption along with minimal carbon footprints (CO_2) would help in getting future sustainable dairy systems together with reaching New Zealand's emission reduction targets[16] under the Paris Agreement. Therefore, the main objectives of this study were:

- To estimate and compare the energy consumption in pastoral and barn dairy systems.
- To estimate and compare the energy carbon footprints of pastoral and barn dairy systems.
- To estimate and compare the energy efficiency of pastoral and barn dairy systems.

Furthermore, the energy research area is under studied in New Zealand, especially from a systems comparative perspective (PDFs versus BDFs). To that end, this study has helped to fill those literature gaps and increase the body of knowledge around energy analysis between contrasting dairy systems of New Zealand. Thus, this thesis provide new insights about energy use, efficiency and carbon footprints of New Zealand PDFs and BDFs dairy systems. Chapter 2 presents the study on evaluation of energy consumption of pastoral (PDFs) and barn (BDFs) dairy farming systems of New Zealand; Chapter 3 presents the work on carbon footprints estimation of PDFs and BDFs dairy systems in an energy context; Chapter 4 presents the study on energy efficiency comparison between NZ contrasting dairy

[16] Under Paris Accord commitments, New Zealand's government proposed a "Zero Carbon Bill" which sets new emissions reduction targets for whole NZ industries including the dairy sector, such as carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions which have to reduce to net zero by 2050, while methane (CH_4) has a reduction target up to 10% by 2030 (DairyNZ, 2019).

systems along with finding energy saving potential for both dairy systems. In this overall conclusions chapter, findings from the case studies are summarized, and recommendations derived for farmers, researchers and policymakers. Furthermore, limitations of the methodology used in this research project are discussed, and potential opportunities for future work are highlighted.

5.2 Energy Consumption Perspective of PDFs and BDFs Dairy Systems

From observation of the study in Chapter 2, where the main purpose of the study was to evaluate the energy consumption of PDFs and BDFs dairy systems of New Zealand, it may be seen that the energy use results for pastoral and barn dairy systems recorded lower energy consumption for PDFs compared to BDFs systems, both per hectare and on a kilogram of milk solids basis. Results showed that PDFs system consumed 9.5% (per ha) and 6% (per kg MS) lower energy inputs than the BDFs system. Compared to each other, use of imported feed supplement energy was higher in BDFs systems while more fertilizer energy was consumed in PDFs systems. The main reasons behind high consumption of feed supplement in BDFs was due to high stocking rate, long lactation period while lower utilization of fertilizer energy was credited to the use of barn facilities in BDFs systems. However, from total energy consumption perception, results are in favour of the New Zealand low-input pastoral based grazing systems, showing that energy can be conserved by 9.5% in PDFs over BDFs systems, through less energy usage.

Further in PDFs systems, electricity (35.5%) was the most important source of energy and fertilizer (29.9%) was the second most important source followed by machinery (15.7%) and imported feed supplements (14.1%). Contrary to that, in BDFs systems after electricity (34.8%) imported feed supplements (24.1%) were the most imperative source of energy. Thus, the main difference in energy consumption of both dairy systems was due to fertilizer and imported feed supplements. Therefore, it is suggested that NZ dairy systems focus more on electricity (both systems), fertilizer (PDFs) and imported feed supplements (BDFs) than the other factors. Hence, better energy management or efficient energy use through new technologies and efficient methods was recommended for reducing energy consumption in both dairy systems.

5.3 Carbon Footprint Viewpoint of PDFs and BDFs Dairy Systems

On observing the study in Chapter 3, where the main purpose of the study was to estimate the carbon footprints of PDFs and BDFs dairy systems in an energy context, it may be seen that the energy carbon footprint for pastoral (PDFs) and barn (BDFs) dairy systems was expressed as carbon dioxide emission in relation to farm area and milk production basis. Comparing pastoral (PDFs) against barn (BDFs) dairy systems, results showed that the BDFs systems have 18% and 11% higher carbon footprints than the PDFs systems, both per hectare of farm area and per ton of milk solids. The greater carbon footprints in BDFs systems was due to higher use of energy inputs such as imported feed supplements, machinery and fossil fuels which released more carbon emission (CO_2) compared to PDFs system.

The difference in both systems indicated that the BDFs systems released 522 ($kgCO_2\ ha^{-1}$) and 209 ($kgCO_2\ tMS^{-1}$) more carbon emission than the PDFs systems, per hectare and per ton milk solids basis respectively, thus, predicting that the NZ pastoral (PDFs) dairy system is more emission efficient compared to barn (BDFs) system. Hence, it can be concluded that there is need to promote the pastoral (PDFs) dairy system due to its emission efficient (CO_2) advantage over the barn (BDFs) dairy system. Moreover, the carbon footprint prediction model highlighted that electricity, nitrogen and sulphur fertilizers and imported feed supplements are the most significant factors in determining carbon footprints of NZ dairy systems. Therefore, from a carbon emission viewpoint, it is necessary for NZ dairy systems to efficiently use their energy inputs particularly electricity, fertilizer and imported feed supplements in order to reduce their carbon footprints (CO_2). Thus, the reduction in carbon footprints through better energy management or by improving energy efficiency was recommended as a solution to reduce overall greenhouse gas emissions from NZ dairy systems in order to achieve future sustainable dairy systems.

5.4 Energy Efficiency Outlook of NZ Dairy Systems

In Chapter 4, the main purpose of the study was comparing energy efficiency of NZ contrasting dairy systems and to find energy saving potential for both dairy systems through optimum energy consumption. In this study, the energy efficiency of New Zealand contrasting dairy systems (PDFs & BDFs) were evaluated through application of the data envelopment analysis (DEA) approach. The results of this study indicated the average TE, PTE and SE of pastoral (PDFs) were 0.84, 0.90, 0.93 respectively and barn (BDFs) dairy systems were 0.78, 0.84, 0.92 respectively, indicating that energy efficiency is slightly better in PDFs compared to BDFs system. In other words, the findings of this study showed that the PDFs system performed technically more efficiently compared to BDFs systems. Moreover, based on results of the CCR and BCC models, 20 (40%) and 24 (48%) dairy farms out of the total dairy farms (50) were performing at a technically inefficient level, highlighting that the majority of farms were consuming higher energy inputs than their optimal point. Thus, inefficient farmers should pay attention to their energy consumption especially electricity, fertilizer and imported feed supplements inputs, to reduce extra use of energy with energy efficiency improvement.

Moreover, the results of optimal energy consumption indicated the potential for 23% and 35% energy savings for PDFs and BDFs respectively. Among energy inputs, electricity and fertilizer have the highest energy saving potential for PDFs systems, while in BDFs systems, imported feed supplement followed by electricity and diesel were the main energy saving inputs. Thus, for energy efficiency improvement in both dairy systems, especially for inefficient dairy farms energy auditing and use of more renewable energy sources were recommended to achieve sustainable and environmentally friendly dairy system for the future of the NZ dairy industry.

5.5 Discussion

New Zealand dairy farming systems should pay attention to their energy expenditure and improve their energy use efficiency to reduce their on-farm energy consumption and associated environmental impacts. To achieve this goal, the NZ dairy industry and policy makers should make the policies and provide incentives to promote energy efficiency and renewable energy usage on NZ dairy farms, to achieve energy and emission efficient dairy system for the future of NZ dairy industry.

Moreover, in comparison to previous NZ dairy energy research, this study indicate that New Zealand pastoral dairy farming systems became more energy intensive over the last years. The main driver of this intensification was expansion of land use area and rising stocking rate, which ultimately result in higher consumption of energy inputs such as fertilizer, feed supplements, electricity etc. However, when compared energy and associated emission profiles of NZ contrasting dairy systems, pastoral system found as energy and carbon emission efficient than the barn dairy system. The main difference was due to higher consumption of fertilizer and imported feed supplements energies in pastoral and barn dairy systems respectively. Since, there is not any study on energy usage of barn system, so no point to compare this study results with previous NZ literature. However, the specific energy results of pastoral dairy system such as energy consumption, carbon emission etc. were compared with previous NZ dairy energy studies, and that's become possible due to application of energy analysis method in this study. For example, when we compared energy consumption results of pastoral dairy system from this study with previous NZ energy studies, it was observed that energy use in pastoral dairy system increased by 38% and 16% respectively, compared to (Barber, 2008; Wells, 2001) studies. Similarly, the energy related carbon footprint of pastoral system observed in this study 36% and 23% higher compared to (Barber, 2008; Wells, 2001) studies. And the leading energy inputs behind this higher energy use and carbon emissions of PDFs systems were electricity, fertilizer and feed supplement inputs. However, limitations of different enery analysis methods and data representative issues make it difficult to compare this study results with international studies.

Furthermore, compared to energy analysis method selected in this study, there is future scope in NZ energy research to apply full Life Cycle Assessment (LCA) approach (cradle to grave) to assess complete energy footprint of different dairy farming systems along with their associated environmental impacts (global warming, acidification, eutrophication). But LCA application will require consideration of complete inventory of farm energy inputs along with post-processing and transport energy components of milk after it leave the farm gate. In other words, more detailed farm energy data is required to apply a true LCA approach on NZ dairy farms. Furthermore, there is not a standard protocol available for the measurement of energy use in farming systems which also make hard comparison between different energy studies. Because some studies considered post-harvesting and transportation as energy inputs and some not. Thus, estimating the national energy equivalents (conversion coefficients) and updating them after a period of time would helpful to increase the accuracy of final energy estimations. In this regard, an international protocol should be developed to clearly identify the inputs and boundaries and standard method for data collection of agricultural energy studies.

It is also important to note that data collection process play a very crucial part in energy analysis studies. Thus, for measuring the energy use and associated emissions of dairy farming systems, designing a suitable survey, choosing the correct number of samples and selecting accurate conversion coefficients are the key factors in energy analysis studies. Therefore, designing a flexible survey and selecting the right method for data collection can help in improving the results accuracy of energy studies.

5.6 Recommendations and Potential Mitigation Options

At present, energy management and environmental sustainability of farming systems are the topics whose importance has been increasing in recent times. In New Zealand, currently reducing environmental emissions from dairy farming systems is a critical challenge for the NZ dairy industry. In this situation, minimizing energy consumption and associated carbon footprints will not only help to achieve energy efficient and environmentally sustainable future dairy systems, but also help in reaching New Zealand's emission reduction target as per the Paris agreement. Thus, a reduction in energy consumption and related carbon footprints through better energy management or by improving energy efficiency would be beneficial and recommended for both types of dairy systems of New Zealand. In this regard, the following are some potential mitigation options for reducing on-farm energy use and related carbon footprints:

- **Electricity:** As irrigation and milking shed equipment are the main electricity consuming events in both dairy systems, using modern and efficient electrical equipment and irrigation methods along with renewable energy resources could provide financial and environmental benefits to farmers through cutting energy use and related costs. Thus, upgrading of older equipment and installation of new energy saving technologies (such as variable speed drives vacuum pumps, milk pre-cooler plates and heat recovery systems from cooling tanks) were recommended for milk harvesting, refrigeration, water heating and lighting purposes. In this regard, an energy audit would be a useful tool for dairy farmers in order to understand their energy usage and identify cost-saving opportunities.

- **Fuel:** As tractors and vehicles are the main fuel users in both systems, so selection of new efficient machinery with minimum tillage techniques or to reduce the number of tractor passes in farming operations could significantly reduce the fuel consumption and related carbon footprints in both dairy systems.

- **Fertilizer:** As fertilizer is one of the most important energy inputs, especially in NZ's pasture based dairy system, among fertilizers, particularly nitrogen is one of the leading sources of carbon emissions in NZ dairy systems. Thus, reduction in fertilizer consumption without affecting crop yield, can provide environmental benefits as well as financial savings for farmers. In this regard, efficiency improvement and better fertilizer management through application of the latest technology such as precision fertilizer application, can play a significant role in reducing both energy and related carbon footprints. Thus, fertilizer management, particularly the type of fertilizer products, method of fertilizer application and the amount of fertilizer usage must be taken into consideration to reduce energy consumption and related carbon footprints from NZ dairy systems.

- **Imported Feed Supplements:** Off-farm the production of imported feed supplements involved, energy inputs such as fossil fuel, fertilizer, machinery and equipment etc., also released carbon dioxide (CO_2) emission into the atmosphere. Thus, changes to feed types (such as grass or maize silage compared to palm kernel or cereal grains), which require less energy for their off-farm production, would lower energy and carbon footprints from NZ dairy systems.

- **Strategic use of off-pasture structures:** In the present study, on average the barn farmers used barn facilities for the duration of 4-6 months with a varying range of 8-14 hours per day, depending upon pasture growth, weather conditions and availability of feed. The main advantage of using barn structure is less fertilizer consumption in the barn dairy system (BDFs), which is due to more effluent collection under barn facilities. However, high installation cost and dependence on volatile milk price may off-set the barn benefits and put barn investment under risk. Contrary to that, fertilizer consumption is high in pastoral systems because of high pasture production. Under these scenarios, there is potential for pastoral dairy systems to achieve some barn benefits through strategic use of off-pasture structures such as feed pad, stand-off pad etc., together with good effluent collection facilities. This may provide better control on effluent under severe weather conditions and delivers benefits such as less soil structure and pasture damages, resulting in less fertilizer consumption due to more effluent collection.

5.7 Limitations

This study used the survey questionnaire method and faced two main limitations, just like other research methods. As in this research project, the method of the survey questionnaire with face-to-face farmers' interviews was used for data collection and the main limitation in the process of data collection was to get true representative data for each type of dairy system. In other words, this type of limitation can be named as sampling error; where survey sample does not represent the population from which it has been drawn. In order to reduce this sampling error, it is necessary to distribute the survey to a true representative sub-population, so that the collected data sample is representative of the larger population (Kelley, Clark, Brown, & Sitzia, 2003). But this is often challenging to achieve, because of difficulty in getting the relevant contact information for people for a required sample. However, to minimize this sampling error, one way is to contact as many relevant people as possible depending upon project funds and time limits. Accordingly, in this research project, we approached as many relevant farmers as possible to minimize the sampling error.

Another unexpected difficulty in this research project was finding barn dairy farmers from Canterbury and especially to convince them (both pastoral and barn dairy farmers) to participate in this research project, as most farmers declined participation due to time constraints and data privacy issues. To address this limitation, personal contacts of Lincoln University staff and the NZ dairy industry professionals were used.

5.8 Future Research work

Findings of this study highlighted the following most important recommendations for future research studies:

- There is a potential to extend this research to explore the energy consumption patterns, environmental impacts and financial costs between different dairy systems such as fully pastoral versus (24 x 7) whole year barn dairy systems, which would help to identify both financially and environmental future sustainable dairy systems. This was beyond the scope of this research work.

- Exploring the impacts of different barn buildings (Freestall, Herdhomes, composting barn etc.) on energy usage would be an interesting topic for future studies. Exploring the further links and relationships between different barn buildings, to include animal health, financial parameters, as well as more in-depth study of greenhouse gas (GHG) emissions (such as energy carbon emissions, methane, nitrous oxide etc.) would help to identify financially viable, emission efficient and animal friendly barn dairy systems.

- Increasing the sample size (especially for barn dairy systems) and testing more variables for a longer time duration, would help to analyze the energy consumption trends for NZ dairy production systems across different regions under different conditions. In this kind of study, the technique of data collection plays a critical role, so special attention needs to be given to data collection methodology. Continuing this study over a longer period of time would help to compare milk and oil prices trends, and their effects on energy consumption and technology use on farms.
- Further to explore the energy usage on the micro-level, research studies performing energy audit methodology for equipment used in NZ dairy farming systems would be highly recommended in order to explore the energy saving opportunities for different farming operations.

- Development of a model and online tool for monitoring and predicting energy intensity, financial cost and related greenhouse gas emissions for NZ farming systems would also an interesting area for future studies, which could be helpful for farmers to monitor, control and predict their on-farm energy usage in order to achieve efficient energy usage.

- Due to climate change and fossil fuel depletion issues in future, research related to use of renewable and non-renewable energy resources in farming systems, along with finding correlations and impacts of renewable energy usage on farming systems would be interesting and recommended for future studies in order to facilitate discussion on peak oil and sustainable agriculture. This research would also helpful in promoting renewable energy usage (solar, biogas) at farm level and would lower agricultural dependence on fossil fuel resources.

- Country-wise comparison between different dairy production systems in terms of energy consumption and related carbon footprints, would also be helpful for the adoption of different farming systems globally. Additionally, this comparison would help in finding the main barriers to reduce energy usage at farm level in each country and globally.

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Appendix A

A.1 Approval letter to conduct survey

Research Management Office

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PO Box 85084, Lincoln University

Lincoln 7647, Christchurch

New Zealand

www.lincoln.ac.nz

4 April 2017

Application No: 2017- 03

Title: Energy consumption and Carbon Footprints of NZ Dairy farming Systems: Comparison of Pastoral & Barn Dairy farming systems

Applicant: H Ilyas

The Lincoln University Human Ethics Committee has reviewed the above noted application.

Thank you for your response to the questions which were forwarded to you on the Committee's behalf.

I am satisfied on the Committee's behalf that the issues of concern have been satisfactorily addressed.

It appears from your response that you may have already initiated the research set out in this application (your response to comment 1c suggests to us that you may have already begun the task of participant selection by contacting an intermediary, and perhaps even have been provided with contacts). Can you clarify if you have already selected participants? On this occasion this minor departure from process will not affect your approval, but please note for future reference that research under application cannot be conducted until you receive approval from the Lincoln University Human Ethics Committee.

Please note that this approval is valid for three years from today's date at which time you will need to reapply for renewal.

Once your field work has finished can you please advise the Human Ethics Secretary, Alison Hind, and confirm that you have complied with the terms of the ethical approval.

May I, on behalf of the Committee, wish you success in your research.

Yours sincerely

Grant Tavinor

Chair, Human Ethics Committee

PLEASE NOTE: The Human Ethics Committee has an audit process in place for applications. Please see 7.3 of the Human Ethics Committee Operating Procedures (ACHE) in the Lincoln University Policies and Procedures Manual for more information.

A.2 Research Information Sheet

Department of Land Management and Systems
Faculty of Agribusiness & Commerce

Lincoln University Survey on Energy Consumption in NZ Dairy Farming Systems

Dear Farmer,

We are conducting research on energy consumption of Pastoral **(PDFs)** and Barn **(BDFs)** dairy farming systems in order to determine their energy use, efficiency and related carbon footprints for the identification of sustainable dairy farming system in New Zealand. This research will helpful for making future energy policies regarding NZ dairy systems.

For the purposes of this study, we are asking farmers like you to give us their views by completing a survey questionnaire for dairy season **2016-17**. The questionnaire covers some background details about your farm and farming system, the infrastructure on your farm (like milking shed), machinery usage, milk production, other inputs use including feed supplements, and some background details about yourself.

Participation is voluntary and the survey is completely anonymous & confidential.

If you agree to participate in this study, please fill attached survey form and returned to me at email: Hafiz.Ilyas@lincolnuni.ac.nz

By completing the questionnaire you are acknowledging that you understand the terms of participation and that you consent to these terms. If you have any queries about the research or wish to make further contribution please do not hesitate to contact us at these email addresses: Hafiz.Ilyas@lincolnuni.ac.nz, Majeed.Safa@lincoln.ac.nz, Alison.Bailey@lincoln.ac.nz

Your cooperation is highly appreciated, thank you for your time.

Best Regards,

Hafiz Ilyas
PhD Research Scholar
Department of Land Management and Systems
Lincoln University
New Zealand

A.3 Survey Questionnaire Used for Data Collection

Department of Land Management and Systems
Faculty of Agribusiness & Commerce

LINCOLN UNIVERSITY
Te Whare Wānaka O Aoraki

SURVEY OF ENERGY CONSUMPTION IN NZ DAIRY FARMING SYSTEMS

Questionnaire Number….. **Data Required: Season 2016-17**
Date: …/…/ …

Dear Farmer

The information you give us is kept "**strictly confidential"** and will not be given any organization, agency, department or person and it has purely academic research. By completing the survey, you will be acknowledging that you understand what is involved in your participation and are providing your consent to participate in the study. Thanks

1- Information about Farm System

The following indicates the **DairyNZ classification of 5 Production Systems**, please tick one option that best applies to your farm:				
All grass self-contained **(System 1)**	Feed imported, either supplement or grazing off **(System 2)**	Feed imported to extend lactation and for dry cows **(System 3)**	Feed imported and used at both ends of lactation and for dry cows **(System 4)**	Imported feed used all year throughout lactation and for dry cows **(System 5)**

If your farm has an **Off-Paddock Shed/Barn Facility,** Please tick one option from the following:		
Loose housed barn-soft bedding material	Loose housed barn-slatted concrete	Free-stall barn

If you farm has an **Off-Paddock Shed/Barn Facility**, Please also specify the following:	
How many weeks feed or kept cows inside shed **(average no. of weeks per year)**	How many weeks feed cows in pasture paddocks **(average no. of weeks per year)**

2- Information about Farm Land and Buildings

Total farm land **(ha)** (i.e. Total dairying area including milking platform, animal runoff, infrastructure etc.)	

Area for milking platform **(Effective ha)**	
Area for animal runoff/support block, if any **(Effective ha)**	
Area for milking shed **(Effective ha)**	
Area for crops grown, if any **(Effective ha)**	

3- Information about Livestock

Type	Type of livestock breeding			Average age (year)	Average weight (kg)
	Jersey (No.)	Friesian (No.)	Crossbred (No.)		
Milking cows on 1st June including heifers & dry cows **(i.e. Peak cows milked)**					
Rising one year old animals (R1)					
Rising two year old animals (R2)					

4-Information about Milk Output for Season 2016-2017

Total Milk Production (kgMS)		Milk Ingredients		
Kg MS/ha	**Kg MS/cow**	**% of Fat**	**% of Protein**	**% of Carbohydrates**

5- Information about Machinery, Equipment's & Vehicles

Name	Brand & Model	Age (years)	Power		Time use (average)	
			HP	kW	hours/day	days/year
Tractor						
Tractor						
Tractor						
Quad Bike						
Quad Bike						

2 wheeler Bikes						
Ute						
Ute						
Others						

6- Information about Milking Parlours

Type	Name of equipment	Brand & model	Sets of cups	Time use (milking+ washing)		Milking/day (No.)
				hours/day	days/year	
Type of Milking system (i.e. Herringbone, Rotary platform, Robotic)						

7- Information about Direct Energy Inputs

Total diesel used per year **(litre)**	
Total petrol used per year **(litre)**	
Total electricity used per year **(Kwh)** Electricity for irrigation Electricity for other farm operations (i.e. milking shed, houses, Barn buildings etc.)	
Labour (Full-time equivalent) Number of employees: Average working hours per day: Average working days per year:	

8- Information about Fertilizer Usage

		Name of Fertiliser Product	Quantity consumed (kg or litre)
Fertilizers (**Kg**) (urea, phosphate, potassium etc.)	**N**		
	P		
	K		
	S		
	Others		

9- Information about Feed Consumption

Feed consumption	**Name** (i.e. ryegrass, clover, cocksfoot, tall fescue, other)	**Feed Produced on farm (kg DM/Year)**	**Feed Purchased outside (Kg DM/Year)**	**Feed consumed per cow (Kg DM/Year)**
Pasture type 1				
Pasture type 2				
Crop 1				
Crop 2				
Supplement 1				
Supplement 2				
Supplement 3				
Supplement 4				
Supplement 5				

Thank you for your time and cooperation.

Appendix B

B.1 Copy of the paper presented and published in 22nd IFMA congress proceeding

CONGRESS SUB THEME: 7. ENVIRONMENT AND RESOURCES

EVALUATION OF ENERGY FOOTPRINT OF PASTORAL AND BARN DAIRY FARMING SYSTEMS IN NEW ZEALAND

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(Paper accepted for congress proceeding and oral presentation, 22nd International Farm Management Association (IFMA) Congress, 3-8 March 2019, Tasmania, Australia)

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Acknowledgements:

The authors gratefully acknowledges support provided by Marvin Pangborn (Lincoln University) and Helen Thoday (DairyNZ) in data collection of this project.

Number of words of the article (excluding tables and references): 3668

Academic paper:

This work is all original research carried out by the authors.

Abstract

Energy consumption is an important component in determining the sustainability of farming practices. Identification of dairy farming systems with efficient energy consumption at the same time as minimising greenhouse gas emissions is vital. In this context, it is relevant to assess the energy footprint of different dairy farming systems in order to identify a sustainable dairy system for the future of NZ dairy industry.

This research is based on comparative analysis of Pastoral (PDFs) and Barn (BDFs) dairy farming systems in Canterbury, New Zealand. A total of 50 dairy farms were investigated, using direct (fuel, electricity, labour) and indirect (fertilizer, feed supplements, machinery and equipment) energy inputs.

The results indicate that PDFs system have 9.5 percent lower energy footprint per hectare than BDFs, mainly due to their greater reliance on pasture based grazing feeding and less use of electricity, fuel and feed supplements. Of interest is that the BDFs use 39% less fertiliser energy but 80% higher feed supplement energy based on the inputs the farmers used. In terms of per kilogram milk solids produced, the PDFs shows 6 % lesser energy footprints compared to BDFs. This research suggests that energy consumption in PDFs in terms of both hectare and milk output is more efficient. However, when considering individual inputs of each system, the energy usage for fertilizer is much higher in PDFs.

Keywords: Energy Footprint, Pastoral Dairy Farming System, Barn Dairy Farming System**,** Canterbury' New Zealand